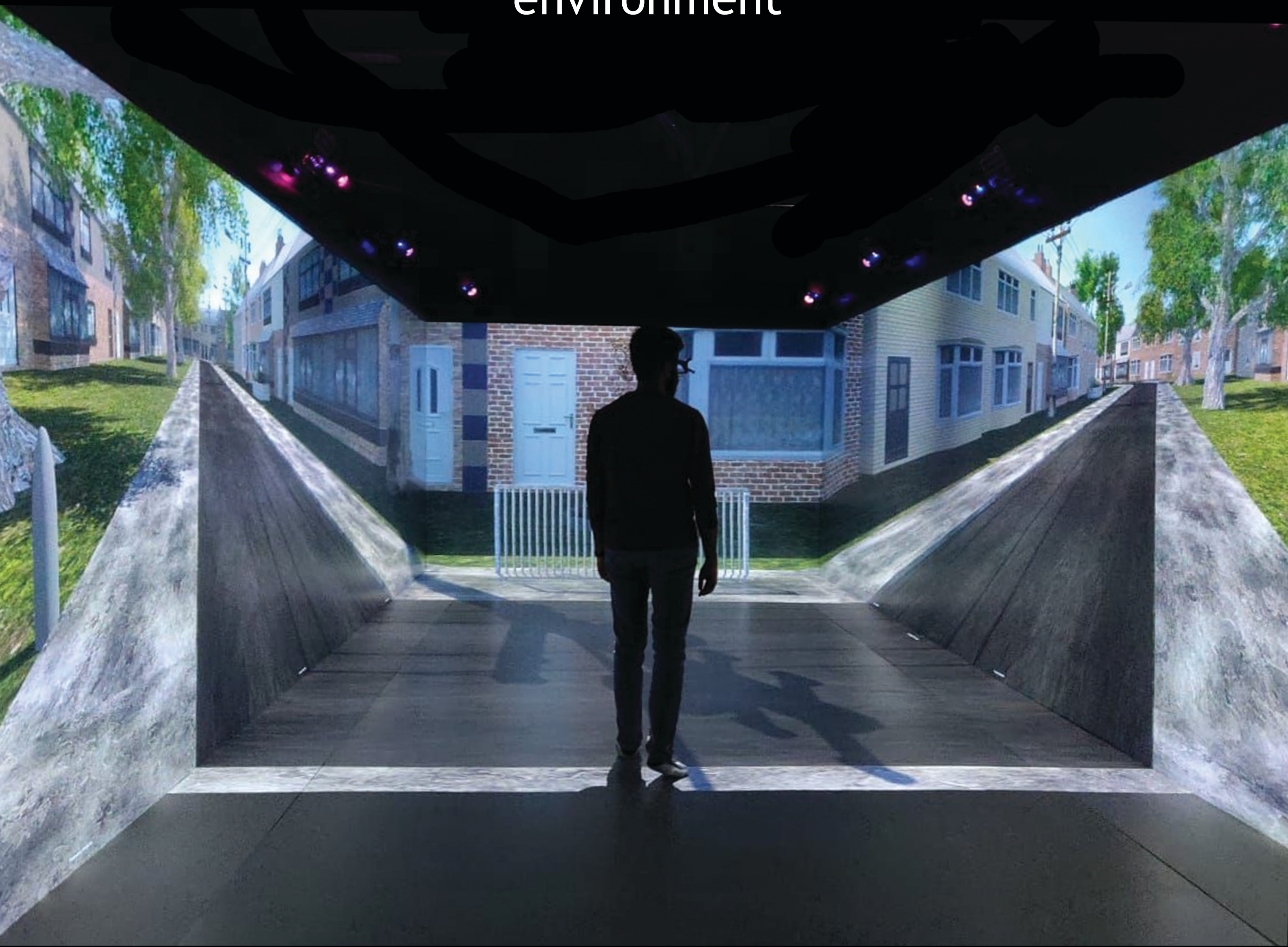
External Human-Machine Interfaces can fail!

An examination of trust development and misuse in a large CAVE-based pedestrian simulation environment



Master thesis

by

Anees Ahamed Kaleefathullah

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External Human-Machine Interfaces can fail!
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Master Thesis

by

Anees Ahamed Kaleefathullah

In partial fulfilment of the requirements

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Personally, I would like to give a big thanks and hugs to my parents Kaleefathullah and Mumtaj, my brother Thameem Ansari, my best friend Sriranjani, her sister Srividya and her mom Shyamli, who have been there for me whenever I needed emotional support. They gave me all the love to make me feel at home even when I'm thousands of miles away from my hometown. Furthermore, I'd like to thank my Delft friends Aneesh, Ashwin, Raj, Madhu, Pragati, Subhiksha, and Saravana who morally supported me during my Masters.

Students writing a thesis might come across difficult times often. But I would like to say that never lose motivation at any cost and *'There are NO shortcuts to achieve your dream. Always strive for progress and perfection.'*

Continue reading the report. There's more interesting stuff coming up ;)

Cheers,
Anees Ahamed Kaleefathullah,
Delft

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ABSTRACT

Aim: In this study, we aimed to investigate pedestrians' trust, crossing behaviour, and misuse of an automated vehicle (AV) equipped with an external human-machine interface (eHMI). We hypothesized that participants' trust would drop to a low level when the eHMI fails (i.e., the eHMI turns on, but the vehicle does not brake), followed by a sustained low of trust in subsequent crossing trials. Furthermore, misuse of the eHMI was expected, operationalized as a situation where participants who are exposed to the eHMI signal before the AV starts to decelerate (-1 group), would start to use the information from the eHMI and cross early instead of relying on the implicit communication from the vehicle. Finally, it was expected that participants who are exposed to the eHMI signals after the AV began to decelerate (+1 group) would be run over by the AV less often when the eHMI fails as compared to participants in the -1 group.

Literature: Prior studies showed that pedestrians tend to overtrust eHMIs, and when there is a malfunction of the eHMI, pedestrians' behavior changed significantly in terms of showing hesitation, longer decision times, and rating an increased risk and reduced trust. However, there is no consensus on the evaluation of pedestrians' overtrust and subsequent misuse of eHMI at different eHMI onset timings.

Methods: We conducted this study at the University of Leeds CAVE simulator. Sixty participants encountered an AV in a typical Britain street virtual environment. The AV was fitted with an eHMI in the form of a 360° light band on the top and sides of the AV and additionally on the grill. The eHMI indicated that the AV has started yielding or is yet to yield for them. All participants experienced fifty trials during the entire experiment. Each trial had a variation of the independent variables: (1) *behavior of the AV*: Yielding with an onset of braking at 33 m and 43 m from the participant, and no yielding, (2) *eHMI state*: On/Off, (3) *eHMI onset timing*: early onset (-1 s) or late onset (+1 s). One half (N = 30) of the participants experienced the early eHMI onset timing (-1 s) where the eHMI turned on 1 s before the vehicle started braking. The other half of the participants (N = 30) experienced the late eHMI onset timing (+1 s) where the eHMI turned on 1 s after the vehicle started braking. After each trial, participants rated three subjective measures (perceived risk, comprehension of the eHMI, and trust in the eHMI) on a scale of 1 (strongly agree) to 10 (strongly disagree). The objective measure was the position of the participant in the simulator.

Results: Participants trusted the AV more with the eHMI than without the eHMI. Furthermore, participants in the -1 group crossed the road considerably earlier than participants in the +1 group. When an eHMI failure occurred, the trust levels and the comprehension of the AV in both groups dropped significantly, whereas self-reported risk rose to high levels. After the first eHMI failure experience, the -1 group trusted the AV with eHMI on significantly less compared to their trust before the failure. Additionally, the results showed that about 30% of the participants in both groups crashed with the AV when the eHMI failed for the first time. There were no significant differences in the number of crashes between the two groups.

Conclusion: Pedestrians' trust considerably reduces when the eHMI fails. Also, there is a sustained loss of trust in the AV's behavior after experiencing the failure in the eHMI. When the eHMI provides early information (before the implicit communication from the AV), pedestrians cross early as compared to the eHMI providing late information (after the implicit communication from the AV). Pedestrians who repeatedly encountered either the 'early' or 'late' onset eHMI crashed with the AV in similar numbers when the eHMI failed for the first time. However, the -1 group managed to avoid crashes when the eHMI failed for the second time.

Application: This study is useful in considering the safety of pedestrians who interact with an eHMI-equipped AV**.**

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Application: This study is useful in considering the safety of pedestrians who interact with an eHMI-equipped AV**.**

Keywords: Autonomous Vehicle (AV), pedestrians, external human-machine interface (eHMI), eHMI failure, trust development, misuse, risk, comprehension, eHMI design, lightband, CAVE simulator

1. INTRODUCTION

1.1. Autonomous Vehicles (AVs) and Vulnerable Road Users (VRUs)

According to the NHTSA, pedestrians constitute 16% of traffic fatalities in 2017, with 73% of these fatalities occurring at non-signalized intersections (National Highway Traffic Safety Administration and National Department of Transportation, 2019). 94% of serious crashes involving pedestrians and drivers are due to human error (National Highway Traffic Safety Administration, 2015). These errors, in most cases, are the result of a driver who fails to yield to the pedestrian or the pedestrian crossing in an unsafe manner. In some cases, the crashes occur due to factors such as adverse road conditions, environmental factors, or technical failures in the vehicle. Autonomous vehicles have the potential to mitigate fatalities that are caused by human error (Fagnant & Kockelman, 2015). Other potential benefits of AVs include improved traffic flow efficiency, productivity, and mobility. However, surveys indicate that the public is still skeptical of buying or using self-driving cars despite the benefits they provide. A large share of the public attributes their skepticism to safety concerns regarding the possibility that the autonomous vehicle system may err, fail, or not function properly (Forbes, October 16, 2019). This concern of safety has become an essential theme in human-AV interaction studies. Even though research is being done to eradicate accidents involving AVs, pedestrians' trust in the AVs remains a relatively unexplored topic (e.g., Jayaraman et al., 2018; Jayaraman, Creech, Tilbury, & Jessie, 2019)

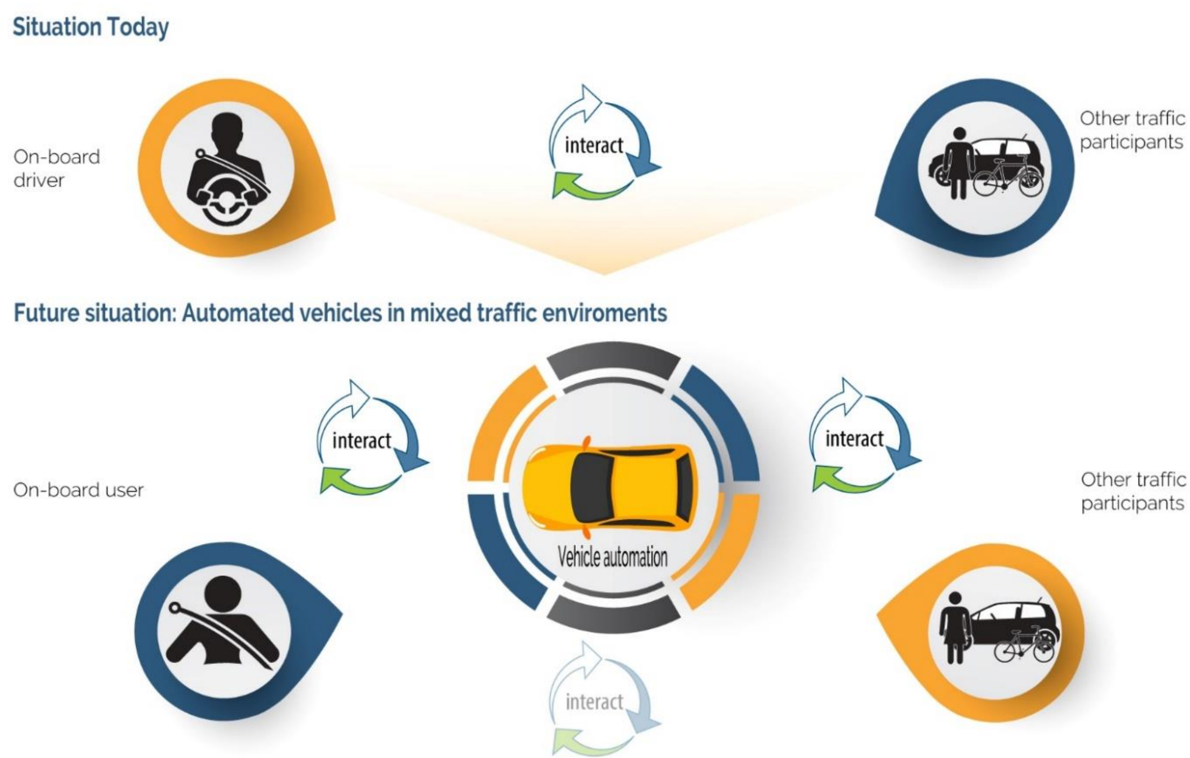

Figure 1. From today's situation of human-human interaction in mixed traffic environments towards a future situation with a triadic interaction between automated vehicles, other traffic participants, and the on-board users (source: EU project interACT) (Schieben et al., 2019)

Currently, pedestrians depend on driver-centric cues (explicit cues) such as eye contact, posture, and hand gestures to interact and cross (Habibovic et al., 2018; Sucha, 2014). Pedestrians' expectations from vehicles influence their decision to cross (Houtenbos, Hagenzieker, Wieringa, & Hale, 2004). However, explicit cues from drivers may be uncommon in pedestrian-vehicle interaction (Dey & Terken, 2017). There are many factors that hinder pedestrians from interacting with drivers, such as bad weather, drivers wearing sunglasses, or glares or reflections from the windshield (Moore, Currano, Strack, & Sirkin, 2019). Some researchers (Dey & Terken, 2017; Moore et al., 2019; Rothenbucher, Li, Sirkin, Mok, & Ju, 2016) argue that pedestrians prefer implicit communication (vehicle-centric information from eHMIs) over explicit communication from the AVs. So, the pedestrians' expectations depend predominantly on implicit cues such as the speed of the approaching vehicle and gap size (Clamann, Aubert, & Cummings, 2017; Sucha, Dostal, & Risser, 2017; Várhelyi, 1998).

In the future, there will be a triadic interaction between the AV, the on-board user, and other traffic participants (see Figure 1; Schieben et al., 2019). Several field studies have evaluated the crossing decisions and behaviors of pedestrians when interacting with vehicles in the absence of a driver (e.g., Clamann et al., 2017; Currano, R. & Park, So Yeon & Domingo, Lawrence & Garcia-Mancilla, Jesus & Santana, Pedro & Gonzalez, Victor & Ju, Wendy., 2018; Rodríguez Palmeiro et al., 2018). In the absence of a driver or passengers on board, explicit communication from humans is out of the question. So, it can be possible to say that even though implicit communication from AV can be an important cue for pedestrians to cross (Moore et al., 2019), it can still be hard for some pedestrians to go entirely without explicit communication. This may make the pedestrian feel unsafe and uncomfortable around AVs. This issue has paved the way for researchers in academia and industries for the development of an artificial form of communication displays, also known as external human-machine interfaces (eHMIs). These eHMIs communicate messages from the AV for a safe and effective pedestrian-AV interaction (Schieben et al., 2019) and are able to provide signals even before implicit communication as in De Clercq et al. (2019) and Eisma et al. (2020). Several researches studies suggest that eHMIs may help pedestrians compensate for the driver's absence and the unpredictable behavior of the AV (e.g. Ackermann, Beggiato, Schubert, & Krems, 2019; Habibovic et al., 2018; Moore et al., 2019) by either explicitly indicating the yielding intention of the AV to the pedestrians through signals or external lights (Song, Lehsing, Fuest, & Bengler, 2018) or by displaying verbal or non-verbal cues for the pedestrians to cross (Bazilinskyy, Dodou, & De Winter, 2019).

Bazilinskyy et al. (2019) surveyed twenty-eight different eHMI concepts. These concepts may show (i) ego-centric perspective information for the pedestrian (see Figure 2), such as Anthropomorphic cues or text such as "Cross" or "Walk" (e.g., De Clercq, Dietrich, Núñez Velasco, De Winter, & Happee, 2019), or (ii) vehicle-centric information (see Figure 2) such as projecting the intention/maneuver of the AV using LED strips or text or numbers or frontal brake lights (e.g., Clamann et al., 2017; Habibovic et al., 2018; Petzoldt, Schleinitz, & Banse, 2018). The perceived safety effects of eHMIs have been investigated by a variety of studies (e.g., De Clercq et al., 2019; Habibovic et al., 2019; Lagstrom & Lundgren, 2015). Additionally, the effect of the eHMI onset timings on perceived safety has been investigated in research by de Clercq et al. (2019), and Eisma et al. (2020). Results from these studies showed that people indicated that they felt safer and more likely to cross when the eHMI indicated a yielding intention at an early eHMI onset timing (i.e., the eHMI turns on before the onset of braking) compared to no eHMI. However, potential overtrust or misuse of the eHMI by the different eHMI onset timings were not evaluated in those studies.


Figure 2: *Left*: Ego-centric information - Smile-shaped light bar on bumper showing pedestrians that it's OK to cross (image taken from Peters, 2016; Semcon, 2016). *Right*: Vehicle-centric information – AVIP (Autonomous vehicles´ interaction with pedestrians) prototype which is a LED strip that lights up in different sequences to communicate that the vehicle is "in automated driving mode", "is about to yield", "is resting" or "is about to start" (copied from Habibovic et al., 2018; Lagstrom & Lundgren, 2015)

At present, pedestrians do not have experience in interacting with AVs and eHMIs on public roads (Hensch, Neumann, Beggiato, Halama, & Krems, 2019). Hensch et al. (2019) discussed that experience in AV/eHMI interaction supports the pedestrians' perceived trust in the AV and eHMI. However, it is possible that pedestrians develop a misplaced trust on the AVs (TheConversation, January 14, 2020) or the eHMI (Rouchitsas & Alm, 2019). Although many papers have demonstrated that eHMIs improve safety and yield a more efficient crossing behavior (e.g., Chang, Toda, Sakamoto, & Igarashi, 2017; Faas, Mathis, & Baumann, 2020; Li, Dikmen, Hussein, Wang, & Burns, 2018) by pedestrians, there appears to be only few studies that investigated and discussed trust and misuse in eHMIs (e.g., Burns, Oliveira, Thomas, Iyer, & Birrell, 2019; Faas & Baumann, 2019; Faas et al., 2020; Holländer, Wintersberger, & Butz, 2019). It is possible that when pedestrians get used to the AV and the eHMI, their trust in vehicle automation increases and might develop into complacent behavior. That is, the pedestrian may start accepting the information from the eHMI as reliable and trustworthy while ignoring implicit communication from the oncoming vehicle. Thus, it is essential to assess the safety of AV-pedestrian interaction at crossings and to assess the development of trust and possible misuse during repeated exposure to eHMIs

1.2. Prior research on trust in automation, AV, and eHMI

A large number of studies have focused on misuse and trust in automation in general (e.g., Bahner, Elepfandt, & Manzey, 2008a; Bahner, Hüper, & Manzey, 2008b; Dzindolet, Peterson, Pomranky, Pierce, & Beck, 2003; Goddard, Roudsari, & Wyatt, 2012; Lee & Moray, 1992; Lee & See, 2004; Parasuraman & Riley, 1997; Reichenbach, Onnasch, & Manzey, 2012). However, there are only a handful of studies on VRU's trust in AVs (e.g., Choi, & Ji, 2015; Creech et al., 2017; Deb, Hudson, Carruth, & Frey, 2018; Dixit, Chand, & Nair, 2016; Jayaraman et al., 2018). Also, there appear to be only a few studies to date that have investigated the effects of trust in eHMI (Burns et al., 2019; Faas & Baumann, 2019; Faas et al., 2020; Holländer et al., 2019).

Automation is often susceptible to failures (Parasuraman & Riley, 1997). When a user overtrusts the automation, he/she may eventually misuse it (Bahner et al., 2008a). Lee and See (2004) provided a schematic diagram showing the relationship between calibration, resolution, and automation capability in defining appropriate trust in automation (see Figure 15 in Appendix A). When automation makes noticeable errors, irrespective of error magnitudes, trust degrades faster even when the automation appears to operate aptly but with silent errors (Madhavan & Wiegmann, 2005).

Trust in Automation. Lee and Moray (1992) investigated the loss and recovery in the operators' trust and performance with continuous and transient faults when interacting with a semi-automatic pasteurization plant. Nineteen participants, divided into four groups, took part in the study for three days (20 trials each day). The experiment had four fault magnitudes (15%, 20%, 30%, and 35%) which concerned a difference between the actual and the target pump rate. Each group experienced at least one fault magnitude. There was one fault in trial 26 in 'day 2', and all trials in 'day 3' had faults. The participants had to respond to rating scales regarding predictability, dependability, faith, and trust on a scale of 1 to 10. Results indicated that the participants' trust and performance increased as they became familiar with the system, i.e., trust developed on day 1 (no faults) while participants learned to control the system. However, when there was a fault on day 2, there was a considerable decline in trust (see Figure 3). Reichenbach et al. (2012) investigated the effects of complacency and trust when interacting with an automation aid. Eighty-eight participants split into four groups out of which only two groups experienced the automation aid and indicated the subjective trust they had on the aid. It was observed that all the participants showed a relatively high trust when the automated aid functioned correctly (see Figure 16 in Appendix A). However, when one of the groups experienced the first failure, trust seemed to decline to a level lower than the initial trust which is also supported by the study by Lee and Moray (1992). Thus, from the above-reviewed papers, it can be inferred that automation reliability affects trust in automation (French, Duenser, & Heathcote, 2018; Lee & Moray, 1992). French et al. (2018) reviewed various literature with regards to trust in automated systems.

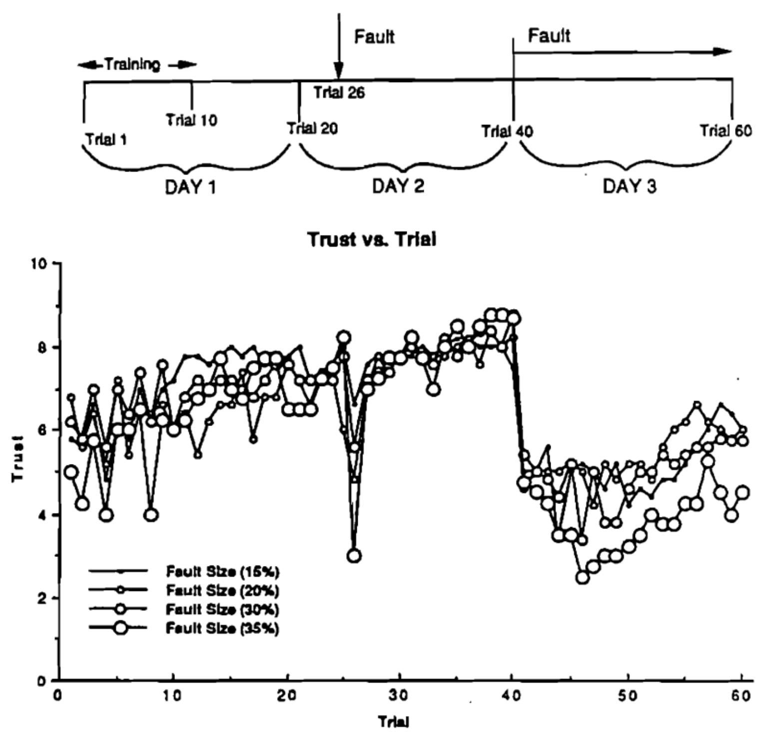

Figure 3: Top: Trials and fault distribution over days. Bottom: The fluctuation in trust over the course of the experiment. Subjective judgment with a maximum possible score of 10, meaning complete trust in the system. (Copied from Lee & Moray, 1992)

Trust in AVs. Walker, Boelhouwer, Alkim, Verwey, and Martens (2018) studied overtrust and overreliance on ADAS (Advanced driver automated system) and examined how drivers' trust in automation can be calibrated to match the actual reliability of SAE level 2 vehicles. One hundred six participants took part in the experiment. A questionnaire was used to measure trust on a 5-point Likert scale before any experience (m0), immediately after the on-road experience (m1) in twelve different driving scenarios (e.g. Scenario 1 – ACC and Lane Keeping; Scenario 2 - brake preceding vehicle…) with the SAE level 2 car, and two weeks after the on-road experience (m2). Results showed that the real-life driving experience led to improvements in trust calibration. Further analyses showed that the drivers showed a significant increase or decrease in the trust in each scenario immediately after the on-road experience (m1) when compared to their experience prior to the driving on-road (m0) (see Figure 17 Appendix A). The authors assumed that the participants overestimated the capabilities of the vehicle before the on-road experience which could have led to the variation in trust before and after the on-road experience. Similarly, Hergeth, Lorenz, Vilimek, and Krems (2016) studied how the drivers' gaze behavior changes with situational, dispositional and learned trust. They used eye-tracking and measured self-reported automation trust to assess the drivers' trust in automation during highly automated driving. Results showed that the participants' road-monitoring frequency during non-driving related tasks was less when their trust in automation was higher and that the decrease in road-monitoring frequency corresponded to an increase in trust in the entire experimental session (see Figure 18 in Appendix A).

Trust in eHMI. A crucial aspect to consider is the long-term psychological effect of eHMIs on pedestrians crossing behavior. Holländer et al. (2019) investigated the effects of an eHMI conveying misleading information on pedestrians' trust. Eighteen participants experienced 12 trials each in a VR study. Participants were split into two groups: (g1) eHMI mismatching display group, and (g2) correct display group. Results showed that the incorrect display in g1 showed a strong decline in trust and perceived safety, but recovered very quickly (see Figure 19 in Appendix A). Our research is an extended version of Holländer et al. (2019) who assessed the overtrust and misuse of eHMI only at a constant eHMI onset time and with only one fault in the entire experiment.

External research on trust in eHMI such as Faas and Baumann (2019) investigated how the color of eHMI affects trust in the eHMI and that a standardized eHMI in an AV will provide a safe and efficient interaction with the pedestrians. Also, Burns et al. (2019) found out that even though the pedestrians understand the intention of the AV through the eHMI, their trust in the eHMI was low. Faas et al. (2020) showed that people trusted the AV more in the presence of an eHMI when compared to no eHMI.

Eisma et al. (2020) and De Clercq et al. (2019) investigated the effects of the eHMI turning on before the AV showing yielding intention on the crossing intention, behavior and the safety of the pedestrians. Their results showed that when pedestrians detected the eHMI much early, they decided to cross earlier. This can be risky as the pedestrians become more vulnerable as they may begin crossing as soon as they encounter the eHMI even before the AV communicates implicitly through its yielding behavior. This stimulates reliance on the eHMI and overestimation of the capability of the eHMI.

The above-reviewed studies show how various external factors such as errors/malfunction, driver behavior, and experience affect users'/pedestrians' trust in various automation applications. However, there seems to be no research regarding (1) overtrust and misuse of eHMIs (except Holländer et al., 2019), (2) the effect of eHMI onset timings on trust, and (3) trust before and after an eHMI failure.

1.3. Aim of this study

According to the above-presented statements on how misuse and overtrust may develop when a pedestrian is repeatedly exposed to eHMI, the following research questions were framed:

1. Do participants develop overtrust/misuse after repeated exposure to a vehicle with an eHMI?
2. To what extent is the degree of overtrust/misuse moderated by the eHMI timing?

The following hypotheses were formulated:

H1: Humans' trust in the AV will be considerably reduced when they encounter a failure of the eHMI (i.e., the eHMI turns on but the vehicle does not yield for the humans).

H2: There will be a *sustained* loss of trust in the behavior of the AV after having experienced a failure in the eHMI

H3: Humans will cross earlier when an eHMI provides 'early' information (i.e., eHMI onset *before* implicit communication from the AV) when compared to an eHMI that provides 'late' information (i.e., eHMI onset *after* implicit communication from the AV).

H4: Humans who have repeatedly encountered an eHMI that provides 'early' information will be more likely to walk under the AV when the eHMI fails (i.e., the eHMI turns on but the vehicle does not yield for the humans) as compared to humans who have repeatedly encountered an eHMI that provides 'late' information

Participants encountered an autonomous vehicle throughout the experiment. Lee et al. (2019) assessed ten different eHMI signal designs, which conveyed the messages 'I am giving way', 'I am in automated mode', and 'I will start moving'. The eHMI options consisted of a 360° lightband, a simple lamp, and an auditory signal. Results showed that for the message 'I am giving way', the fast pulsing lightband and the conventional flashing headlights were most preferred. So, according to the requirements of the interACT project (Kaup et al., 2018), our study had an AV with a 360° fast-pulsing LED lightband located on the front and sides of the vehicle as well as on the grill. This positioning would enable the pedestrian to be aware of the light band from any approaching direction (Lee at al., 2019).

To test the hypotheses, the following independent variables were manipulated: (1) the yielding behavior of the vehicle (yielding at 33 m from the participant, yielding at 43 m from the participant, and no yielding), (2) the eHMI onset: Early onset (-1 s from the moment of decelerating) and late onset (+1 s from the moment of decelerating), and (3) the eHMI presence (eHMI off vs. on).

The experiment was conducted in a CAVE (Cave Automatic Virtual Environment) simulator, also known as 'HIKER', at the Institute for Transport Studies, University of Leeds. The CAVE simulator allowed the participant to experience an immersive virtual reality road crossing environment. A number of studies have previously studied the crossing behavior/ intention of pedestrians in a CAVE simulator (e.g., Cavallo, Dommes, Dang, & Vienne, 2019; Dommes, Cavallo, Dubuisson, Tournier, & Vienne, 2014; Rahimian et al., 2016) and using head-mounted displays (e.g., Chang et al., 2017; Creech et al., 2017; De Clercq et al., 2019; Holländer et al., 2019). However, trust in AV and eHMI have not been evaluated in a CAVE simulator before. We believe that a realistic simulation environment such as in 'HIKER' is important for an accurate humans' risk perception of eHMIs (for example, instead of just merely rating the clarity of eHMI concepts) as they make decisions voluntarily. The data collection and pedestrian experience vary by a few factors from head-mounted display studies. The HIKER's fidelity was analyzed by asking the participants to fill in a post-experiment questionnaire 'presence questionnaire'

2. METHODS

2.1. Participants

Sixty participants (thirty males and thirty females) aged between 18 to 36 years (*M* = 24.4; *SD* = 4.02) participated in the study. They were recruited via posters at the University of Leeds student union, through acquaintances, and posts on social media. The criteria to participate were that participants must have lived in the UK for at least a year and not suffer from motion sickness, mobility problems, or epilepsy. The sixty participants had fifteen different nationalities: one Brazilian, six Chinese, one Greek, one Iranian, three Lithuanian, twenty-eight British, one Zimbabwean, one German, three French, two Indian, one Irish, one Italian, five Malaysian, three Polish, and three Spanish. The participants were professional workers, students, or University staff.

The participants were asked to indicate whether they are used to left-hand traffic or right-hand traffic. From the sixty responses in the pre-experiment questionnaire, twenty-eight participants were used to left-hand traffic, fifteen participants were used to right-hand traffic, and the remaining sixteen participants were used to both left- and right-hand traffic. Twenty-one participants wore their personal glasses during the experiment. Thirty-seven participants had experience with head-mounted virtual reality.

Ethical approval was obtained from the University of Leeds Research Ethics Committee (Ref: LTTRAN-097). All participants provided written informed consent.

2.2. Simulator

The study was conducted in the newly built HIKER (Highly Immersive Kinematic Experimental Research) pedestrian simulator (see Figure 4) at the University of Leeds. The pedestrian simulator is a CAVE-type simulator of 9 m x 4 m. Participants wore stereoscopic motion-tracking glasses and were handsfree. The virtual environment featured a single lane road of 4.2 m wide in a city environment during daytime (Figure 4). In each trial, a blue car approached from the corner on the participant's right. A fence was placed on the other side of the road on the pavement to prevent the participant from crossing beyond that. The simulator was programmed to alert the participant with a warning sound when being close to the walls.

The walls of the HIKER lab are thick plate glass with rear projection from an array of eight projectors, with the whole scene responding to the participants' head position and gaze. For being able to run the cave system, the facility counts with a rack of nine computers: one for general management and development, and a dedicated one for each of the eight projectors. They are all connected via a KVM switch to facilitate general management.

All nine computers are identical and have the following specifications:

- Intel® Core™ i9-7900X CPU @ 3.30GHz
- 128 GB Ram DDR4
- NVIDIA Quadro P4000 - 8GB GPU
- Windows 10 Pro desktop

The scenario was generated in Unity 2017.4.17 with a Middle VR 1.7.1.2 licensed plugin. All projectors generated the scenario in stereo mode at a resolution of 2560 x 1600. Eight IR motion trackers, which ran with Vicon Tracker 3.7, tracked the position and head rotation angle of the participant wearing stereoscopic glasses having reflective ball markers.

Figure 4. The HIKER pedestrian simulator. *Left*: View from the pedestrian's starting position. *Right*: View towards the right, from where the vehicle is approaching.

2.3. Experimental Design

The experiment was of a mixed design. The independent variables were (1) the eHMI onset (-1 s and +1 s), (2) the yielding behavior of the vehicle (yielding while starting to decelerate at a 33 m distance, yielding while starting to decelerate at a 43 m, and No yielding), and (3) the eHMI presence (eHMI off vs. on).

Each participant performed 50 trials. In each trial, the participant encountered a fully autonomous blue car. Four blocks were made of 12 trials each. In addition, there was one failure trial after Block 3 and one after Block 4 (see Table 1). In the failure trial, the eHMI turned on, but the vehicle did not yield for the pedestrian. Once the participant triggered the start of the trial, the vehicle approached around the corner on the right at a speed of 30 mph (48.3 km/h).

Table 1.
Experimental blocks

Block 1	**Block 2**	**Block 3**	**Failure trial 1**	**Block 4**	**Failure trial 2**
Trials 1–12	Trials 13–24	Trials 25–36	Trial 37	Trial 38–49	Trial 50

eHMI onset. The eHMI onset was a between-subjects variable. The odd-numbered participants and even-numbered participants were assigned to Group 1 and Group 2, respectively. Group 1 had a +1 s eHMI onset; that is, the eHMI turned on 1 s after the vehicle started to decelerate. Group 2 has a -1 s eHMI onset where the eHMI turned on 1 s before the vehicle started to decelerate.

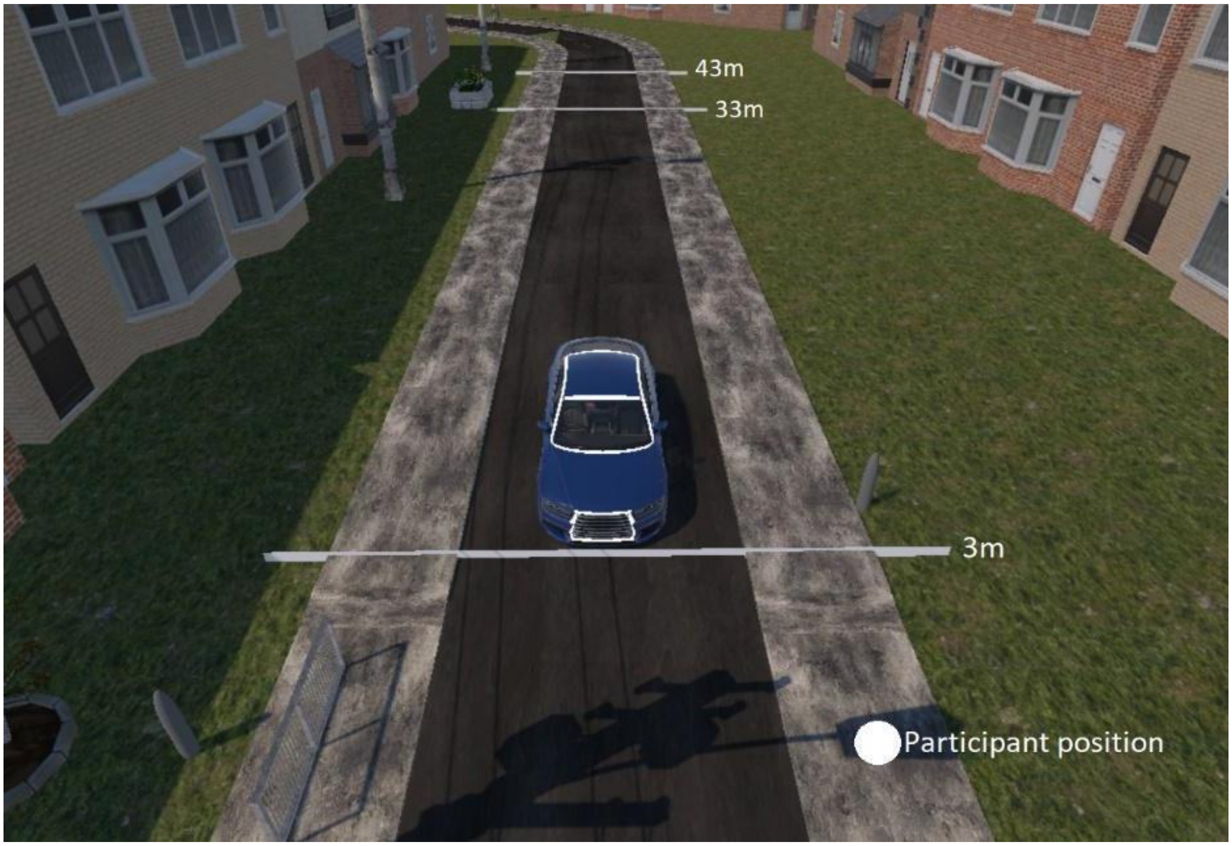

Figure 5. The lines display the distances where the vehicle started to decelerate (33 m and 43 m) and the complete stop at 3 m from the participant. The white circle indicates the participant's initial position. Note that the white lines and circles were not visible during the experiment.

Yielding behavior. The yielding behavior was a within-subject variable. The vehicle decelerated at 2.24 m/s^2 and 2.99 m/s^2 for stopping distances of 43 m and 33 m, respectively. During yielding trials in a block, the vehicle came to a complete stop at a distance of 3 m from the participant (see Figure 5) and waited until the pedestrian crossed and then drove off again. If the participants crossed before the vehicle came to a complete stop, the car accelerated again without stopping. During non-yielding trials (4 trials with the eHMI off), the vehicle maintained a speed of 48.3 km/h without stopping for the participant. Table 2 provides an overview of the number of trials per yielding condition within each block. The order of trials was random within each block for all blocks and different for each participant. The speed vs. distance for both groups with two stopping distances and two eHMI onsets is shown in Figure 6. The distance between the pedestrian and the approaching vehicle is taken along the *x*-axis (i.e., parallel to the direction of the road).

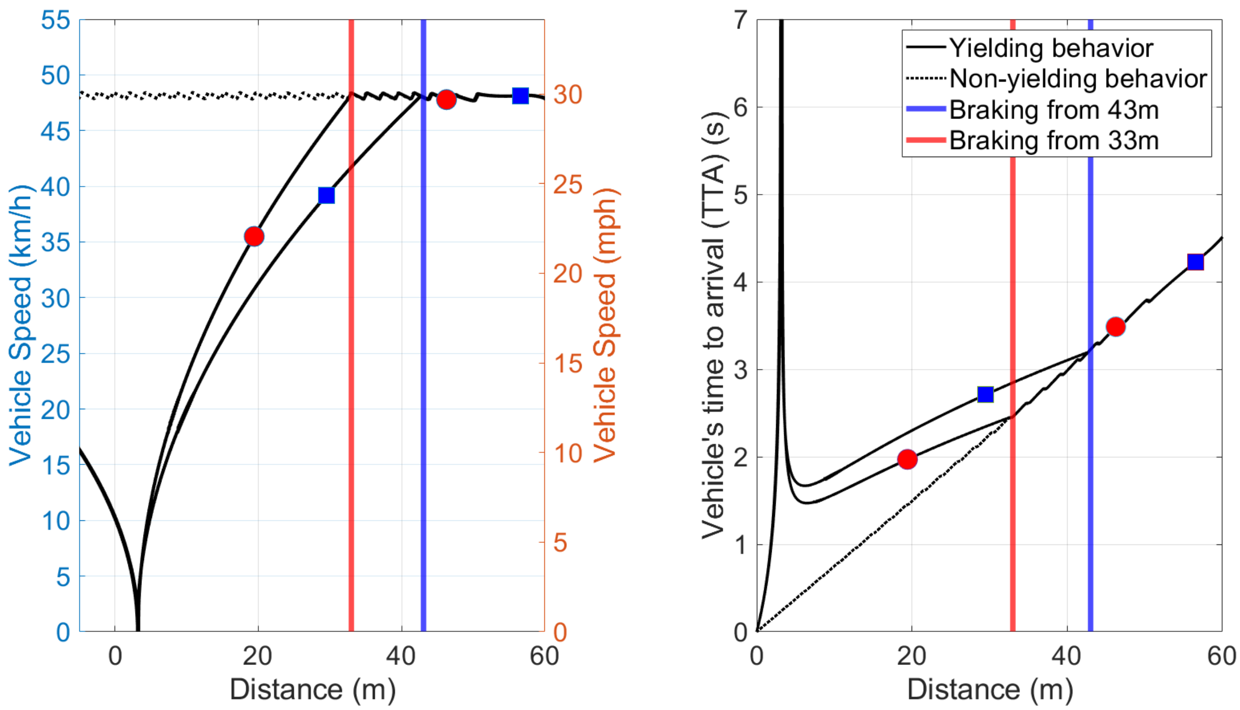

Figure 6. Left: Vehicle speed vs. Distance; Right: Vehicle's time to arrival (TTA) vs. distance. The red markers indicate the onset of the eHMI at -1 s and +1 s, calculated from the moment of deceleration at 33 m from the pedestrian. The blue markers indicate the onset of the eHMI at -1 s and +1 s, calculated from the moment of deceleration at 43 m from the pedestrian.

eHMI presence. The eHMI presence was a within-subject variable. In yielding trials, the eHMI was on in 75% of the cases, and off in 25% of the cases (see Table 2). The eHMI consisted of a light band around the top edges of the car and on the front grill, as shown in Figure 7. The intensity of the eHMI light band pulsated in a zigzag-like manner between 30% and 100%. The intensity was 100% at the onset of the eHMI and the intensity peak-to-peak interval was 0.8 s. This light band intensity variation started from the moment the vehicle started to decelerate. It lasted until the moment the participant finished crossing. In failure trials, the eHMI pulsing continued until the car drove off to the other end of the road until it disappeared from the participant.

Table 2.
Number of trials per yielding behavior condition and eHMI presence condition within each block of 12 trials.

Distance between pedestrian and vehicle at the onset of deceleration	eHMI presence	Number of trials per block
33 m	On	3
43 m	On	3
33 m	Off	1
43 m	Off	1
No yielding	Off	4

Figure 7. Autonomous vehicle. Left: eHMI on (100% intensity). Right: eHMI off.

In the two failure trials, the eHMI switched on at 38 m (average onset distance of the two groups) from the participant, but the vehicle did not yield. The eHMI timing for the failure trial was the same for Groups 1 and 2.

2.4. Dependent Variables

The dependent variables include subjective measures regarding risk, comprehension, and trust. More specifically, the following three questions were displayed after each trial (see Figure 8):

1. I experienced the situation as risky
2. I could comprehend the behavior and appearance of the approaching vehicle
3. I trust the behavior and appearance of the automated vehicle

These post-trial questions were answered on a scale of 1 (Strongly Disagree) to 10 (Strongly agree).

Additionally, we computed the pedestrian's walking distance in the *z*-direction (i.e., perpendicular to the road) as a function of elapsed time. The following dependent variables were extracted from the logged files:

- Pedestrian's walking distance, defined as the walking distance in meters 7.5 seconds into the trial. This measure can be seen as an indicator of the participant's trust in crossing. This measure was computed only for trials in which the vehicle was yielding for the participant.
- Crash (0 or 1). For each trial in which the vehicle did not yield, we computed whether the pedestrian walked in front of the car or not. Note that other measures such as time to collision (TTC) were not found to be useful because the vehicle drove fast (48.3 km/h); if the participant stepped onto the road in front of the car, this would almost always yield a crash (TTC = 0 s). Hence, a binary measure of crashes versus not crashing was regarded as most appropriate for describing the participant's experienced risk in non-yielding trials.

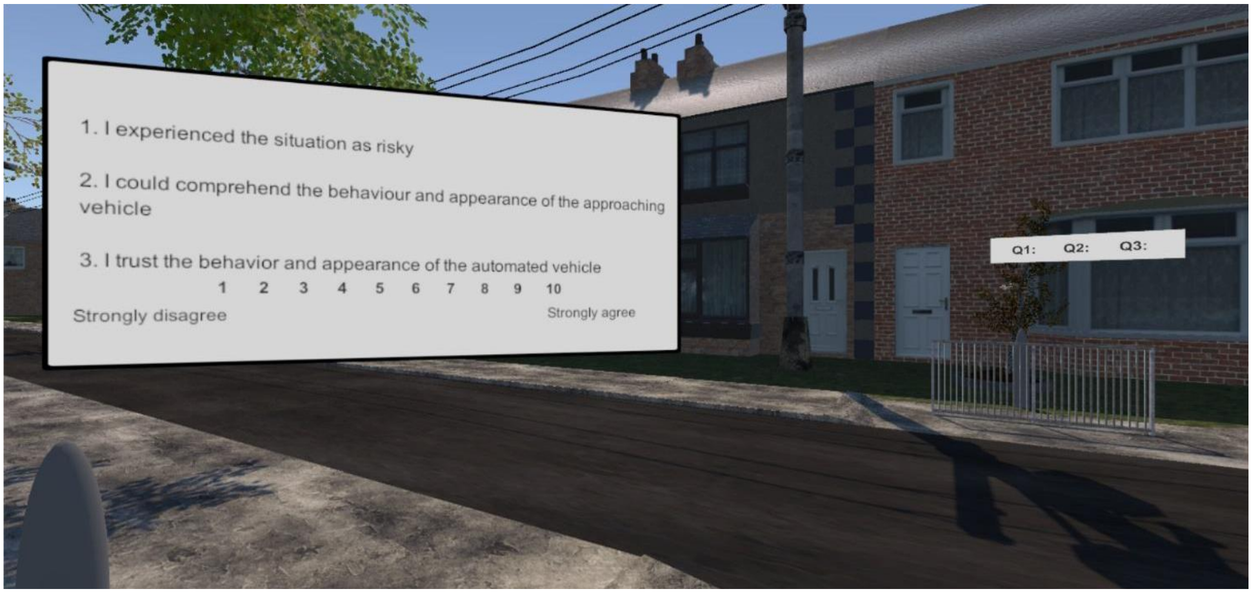

Figure 8. Post-trial questions displayed on the participant's left. Each question was answered verbally on a scale from 1 (Strongly Disagree) to 10 (Strongly agree).

2.5. Procedure

Every participant went through the same process during their participation: consent form, pre-experiment questionnaire, practice session, main experiment, post-experiment questionnaire.

The study lasted approximately one hour per participant. After the participants entered the HIKER room, they were first given a general overview by the researcher that this is an experiment aiming to study the crossing behavior of pedestrians when they interact with autonomous vehicles.

The participants were asked to read and sign the informed consent form, which also contained the task instructions. The task instructions were described as follows:

1) *With the glasses on, you will look to the corner on the right and take one or two steps forward. The car will then appear from the right corner*
2) *You will then move forward along the pavement and then decide to cross or not depending on the yielding behavior of the vehicle*
3) *At the end of each trial, irrespective of crossing or not, you'll need to answer 3 questions (displayed on the left wall of the simulator) on a scale of 1 to 10.*

Next, participants were asked to complete a pre-experiment questionnaire consisting of general information of the participant, which took approximately 3 minutes.

All participants experienced the same eHMI and yielding behavior of the vehicle irrespective of their group during the practice session. The practice trials consisted of five trials: three trials with a non-yielding vehicle, one trial with the eHMI on with a yielding vehicle, and one trial with eHMI off with a yielding vehicle. The participants were verbally briefed again by the researcher in the simulator with step-by-step instructions on triggering the car, on how and when to cross the road, and on how to answer the post-trial questions. The purpose of the practice session was to make sure that the participant was clear of any questions regarding the task.

Before entering the simulator, the participants removed their shoes and wore stereoscopic glasses. They initially stood on the near edge of the pedestrian simulator. They then walked forward towards the opposite side of the road, while looking to the right corner from where the car would approach. The head rotation of the participants is being measured by the simulator. The trigger of the car is achieved when the participants rotate their head at any angle greater than 45 degrees to their right and move forward through a programmed invisible trigger collider. The car then started approaching. The participants moved forward along the pavement and decided to cross or not cross. After crossing, the participants then returned to the starting position of the simulator. Irrespective of crossing or not crossing, the participants verbally rated the three post-trial questions that appeared on their left, as shown in Figure 8. Once they rated the questions, they got ready to start with the next trial.

After completion of the experiment, the participants were asked to complete the post-experiment questionnaire, which took approximately 10 minutes. The post-experiment questionnaire consisted of questions regarding the experiment in general, the external light band, and a set of virtual presence questions (Witmer & Singer, 1998). They were then reimbursed with 10 GBP.

2.6. Statistical Analyses and participant exclusion

All data were post-processed in MATLAB R2019b. Apart from the subjective measures, the pedestrian *z*-position at 7.5 s was retrieved for all yielding trials. The pedestrian *z*-position indicates how far participants had walked towards the road in the midst of a yielding trial.

Participants who crashed in more than 6 out of 18 non-yielding trials were excluded for analysis and plotting in all dependent variables.

A table was constructed containing the mean scores of the dependent variables, separated per block, eHMI presence, and yielding behavior, of all participants. The *p*-values from paired-samples (for within-group comparisons) and independent-samples t-tests (to compare the -1 and +1 groups) are also provided in the table. We used a significance level (alpha) of 0.01.

To evaluate the hypotheses, the following comparisons were made between conditions for each of the dependent variables:

- eHMI on vs. eHMI off (separately for each block, stopping distance, and eHMI onset group). This is a within-group comparison.
- Block 3 vs. 4, to examine whether the failure trial affected participants' subsequent behavior (separately for each yielding behavior and eHMI onset). This is a within-group comparison.
- eHMI onset -1 s vs. +1 s (separately for each block, and stopping distance). This is a between-groups comparison.
- Percentage of crashes -1 s vs. +1 s (for all non-yielding trials including failure trial). This is a between-groups comparison using Fisher's exact test.

Data was represented in plots as follows:

1. Mean z-position of the participant per yielding condition as a function of elapsed time
2. The variation of pedestrian z at 7.5 s in block 3 and 4

3. Mean scores of (a) risk, (b) comprehension, (c) trust, and mean distance of (d) pedestrian z at 7.5 s
4. The percentage of crashes during non-yielding trials. A crash was defined as a situation where the pedestrian *z*-position was between 2.050 and 6.239 m (i.e., between the edges of the road) while the vehicle was passing.

Finally, a table with the mean and standard deviation of the scores of the participants' responses of all questions in the presence questionnaire was made.

3. RESULTS

Data of six participants (four in the +1 group, and two in the -1 group) who crashed in more than 6 out of 18 non-yielding trials in Blocks 1–3 were excluded for analysis and plotting. According to the observations by the researcher in the experiment,

- Participant 6 was too fast in crossing and crossed in all trials irrespective of the yielding behavior of the car
- Participant 7 commented that he forgot that the car was automated despite the instructions given at the start of the experiment
- Participant 14, 17, and 31 showed signs of inadvertent crossings and hesitated too much in the middle of their crossing leading to crashes with the AV in most non-yielding trials
- Participant 41 was young and careless in his crossing. He crossed earlier, similar to participant 6 and at all trials. When asked why he performed carelessly, he commented that he always expects the AV to stop for him in real life and he expected the same behavior in the simulator

Table 3.

Mean scores and p-values of the dependent variables per condition per block. The blue highlighted numbers are statistically significant p-values < 0.01.

SUBJECTIVE AND OBJECTIVE MEASURE MEANS
Highlighted in blue: paired t-test; Significance at *p < 0.01*

		Group +1					Group -1				
		33, On	33, Off	43, On	43, Off	NY, Off	33, On	33, Off	43, On	43, Off	NY, Off
RISK (1 to 10)	Block 1	4.09	4.96	3.08	4.54	5.98	3.25	5.14	2.75	5.11	5.09
	Block 2	4.01	4.19	3.14	4.35	5.78	3.00	5.00	2.37	4.82	4.72
	Block 3	3.82	4.46	2.97	4.38	5.83	2.67	4.96	2.21	4.57	4.73
	Block 4	3.97	4.15	3.19	4.23	5.62	3.49	4.64	2.74	4.11	4.35
	Failure trial 1	8.88					8.68				
	Failure trial 2	8.65					7.79				
	p-value Block 3 vs. 4	3.89E-01	1.88E-01	3.99E-01	7.06E-01	2.74E-01	1.88E-03	2.79E-01	4.18E-02	1.47E-01	9.43E-02
		33, On	33, Off	43, On	43, Off	NY, Off	33, On	33, Off	43, On	43, Off	NY, Off
COMPREHENSION (1 to 10)	Block 1	6.71	5.88	7.87	6.12	6.67	7.85	4.96	8.19	5.54	6.40
	Block 2	6.87	5.77	7.90	6.15	6.80	8.10	5.43	8.70	6.07	6.29
	Block 3	7.01	6.12	8.22	6.38	6.72	8.29	5.46	8.69	6.11	6.65
	Block 4	7.06	6.38	7.99	6.50	6.93	7.39	5.96	8.12	6.29	6.73
	Failure trial 1	3.23					2.00				
	Failure trial 2	3.85					2.57				
	p-value Block 3 vs. 4	7.86E-01	4.17E-01	3.24E-01	8.29E-01	2.02E-01	6.59E-04	2.26E-01	3.11E-02	5.38E-01	5.60E-01
		33, On	33, Off	43, On	43, Off	NY, Off	33, On	33, Off	43, On	43, Off	NY, Off
TRUST (1 to 10)	Block 1	6.53	5.77	7.65	6.08	5.76	7.35	5.39	7.87	5.64	5.81
	Block 2	6.74	5.92	7.82	6.08	5.95	7.58	5.46	8.29	6.04	5.91
	Block 3	6.74	6.35	7.97	6.27	5.88	7.83	5.50	8.39	5.57	6.10
	Block 4	6.55	6.27	7.24	6.58	5.96	6.45	5.32	7.35	6.04	6.07
	Failure trial 1	2.38					1.64				
	Failure trial 2	2.12					1.71				
	p-value Block 3 vs. 4	5.07E-01	7.91E-01	3.36E-02	4.30E-01	6.62E-01	6.13E-04	4.94E-01	2.92E-03	9.65E-02	8.65E-01
		33, On	33, Off	43, On	43, Off		33, On	33, Off	43, On	43, Off	
PEDESTRIAN Z AT 7.5 SECONDS (m)	Block 1	2.37	1.85	3.18	2.10		3.61	1.92	4.10	2.47	
	Block 2	2.44	2.15	3.17	2.16		4.00	2.02	4.58	2.33	
	Block 3	2.71	2.08	3.30	2.34		3.88	2.09	4.58	2.33	
	Block 4	2.47	2.21	2.88	2.33		2.85	2.13	4.01	2.41	
		0.00									
	p-value Block 3 vs. 4	3.17E-02	7.23E-02	6.58E-04	9.41E-01		2.94E-05	7.18E-01	1.39E-02	6.72E-01	

Note. For representation purposes, the values are conditionally color-coded using a graded color scale to show the lowest to highest perceived risk, and the highest to lowest comprehensibility of, and trust in the eHMI. The red color coding indicates the critical values of the measures.

Table 3. *(continued)*
p-values of the dependent variables per condition per block

Highlighted in blue: t-test; Significance at $p < 0.01$

		p-values					
		Group + 1 s vs. -1 s		eHMI On vs. Off		eHMI On vs. Off	
		33, On	43, On	33, +1	43, +1	33, -1	43, -1
RISK (1 to 10)	Block 1	1.18E-01	5.12E-01	2.44E-02	**4.63E-03**	**5.79E-04**	**3.26E-05**
	Block 2	4.47E-02	1.35E-01	6.62E-01	**5.95E-03**	**1.37E-04**	**1.39E-06**
	Block 3	2.76E-02	1.10E-01	7.57E-02	**1.45E-03**	**6.24E-06**	**1.26E-05**
	Block 4	3.92E-01	3.81E-01	5.77E-01	**7.83E-03**	**6.41E-03**	**3.49E-04**
	Failure trial 1	7.12E-01					
	Failure trial 2	1.92E-01					
		Group + 1 s vs. -1 s		eHMI On vs. Off		eHMI On vs. Off	
		33, On	43, On	33, +1	43, +1	33, -1	43, -1
COMPREHENSION (1 to 10)	Block 1	1.13E-02	4.77E-01	2.33E-02	**7.88E-05**	**1.27E-06**	**1.75E-07**
	Block 2	**5.63E-03**	6.00E-02	1.15E-02	**4.98E-04**	**8.53E-05**	**4.28E-06**
	Block 3	**4.92E-03**	1.92E-01	3.94E-02	**1.17E-04**	**1.10E-05**	**5.94E-07**
	Block 4	4.53E-01	7.46E-01	4.22E-02	**7.67E-04**	**2.01E-03**	**1.22E-04**
	Failure trial 1	9.30E-02					
	Failure trial 2	6.65E-02					
		Group + 1 s vs. -1 s		eHMI On vs. Off		eHMI On vs. Off	
		33, On	43, On	33, +1	43, +1	33, -1	43, -1
TRUST (1 to 10)	Block 1	1.18E-01	6.67E-01	1.22E-01	**1.00E-03**	**2.02E-04**	**4.76E-06**
	Block 2	9.20E-02	3.29E-01	2.11E-02	**3.70E-05**	**7.09E-04**	**1.50E-05**
	Block 3	2.88E-02	3.31E-01	3.15E-01	**4.39E-04**	**1.60E-04**	**1.80E-07**
	Block 4	8.53E-01	8.46E-01	3.47E-01	2.26E-02	1.53E-02	5.26E-03
	Failure trial 1	1.56E-01					
	Failure trial 2	3.84E-01					
		Group + 1 s vs. -1 s		eHMI On vs. Off		eHMI On vs. Off	
		33, On	43, On	33, +1	43, +1	33, -1	43, -1
PEDESTRIAN Z AT 7.5 SECONDS (m)	Block 1	**1.77E-03**	4.24E-02	**4.31E-05**	**4.14E-06**	**4.45E-06**	**1.67E-05**
	Block 2	**3.67E-04**	**6.09E-03**	**6.60E-04**	**5.55E-06**	**1.49E-06**	**1.41E-06**
	Block 3	**7.46E-03**	**8.17E-03**	**1.23E-04**	**4.72E-06**	**1.16E-06**	**8.58E-08**
	Block 4	2.67E-01	1.43E-02	**7.41E-03**	**4.62E-04**	**2.14E-03**	**1.49E-06**

3.1. *Comparison between eHMI On and Off states*

Table 3 shows the mean scores of the dependent variables, separated per block (1 to 4), eHMI presence (On or Off), and yielding behavior (33 m, 44 m, or no yielding). It can be seen that the perceived risk levels were lower when the eHMI was On compared to when it was Off. Similar effects were found for perceived comprehension and trust, with higher trust and comprehension for eHMI On compared to eHMI Off. Pairwise comparisons (i.e., paired *t*-tests) per block for the subjective measures show significant differences in risk, comprehension, and trust between the eHMI On and eHMI Off, except for the 33 m condition of the +1 group.

The pedestrian *z* at 7.5 s values indicate that the participants walked further towards the road in the eHMI On conditions as compared to the eHMI Off conditions. Paired *t*-tests per block showed significant differences between the eHMI On and Off states in the 43 m and 33 m stopping distances for both groups. These effects are illustrated in Figure 9, showing the mean pedestrian *z* position as a function of elapsed time for all yielding conditions.

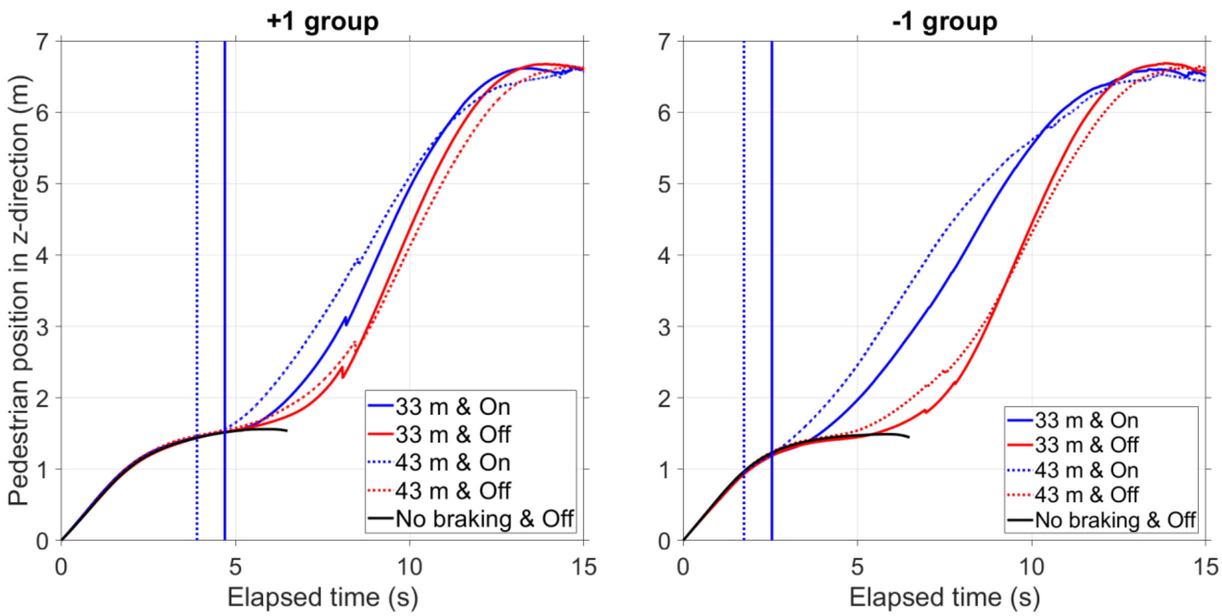

Figure 9. Mean Pedestrian z-position as a function of elapsed time per group, yielding condition, and eHMI condition. The vertical lines represent the eHMI onset times for the 33 m and 43 m stopping distances.

3.2. Comparison between Block 3 and Block 4

Figure 10 illustrates how the subjective measures (participants' mean scores of risk, comprehension, and trust) increased and decreased during the experiment. Participants got used to the proper functioning of eHMI during the first three blocks (See also Table 3 for an increase in trust for Blocks 1 to 3).

Table 3 and Figure 10 show that for both groups, in Failure trial 1 (post Block 3) and Failure trial 2 (post Block 4), risk had a substantial increase, and comprehension and trust had a considerable decrease as compared to the other trials. More specifically, the participants' mean risk levels for failure trials were between 7.79 and 8.88 on a scale from 1 to 10, indicating that participants perceived a high level of risk. Trust, on the other hand, was low (between 1.64 and 2.38) for the failure trials. Paired t-tests of the perceived risk, comprehension and trust for the failure trials showed no significant differences between the +1 group and the -1 group (Table 3). We hypothesized that trust declines considerably when there is a failure in the eHMI (H1). This hypothesis was confirmed by the results in Table 3 and Figure 10(c).

We hypothesized that there would be a loss of trust after experiencing a failure in the eHMI (H2). To prove this hypothesis, we examined the differences between Block 3 (before the failure trial) and Block 4 (after the failure trial). Table 3 shows that in Block 4, the risk was generally higher, and comprehension and trust lower, as compared to Block 3. The block 3 vs. block 4 differences were generally not statistically significant for the +1 group, but significant for the -1 Group, especially in the '33 m On' condition. Furthermore, paired *t*-tests showed that, in the '43 m On' condition of the +1 group, the participants walked significantly less far in Block 4 compared to Block 3. Similarly, in the '33 m On' condition' of the -1 group, the participants walked significantly less far in Block 4 compared to Block 3.

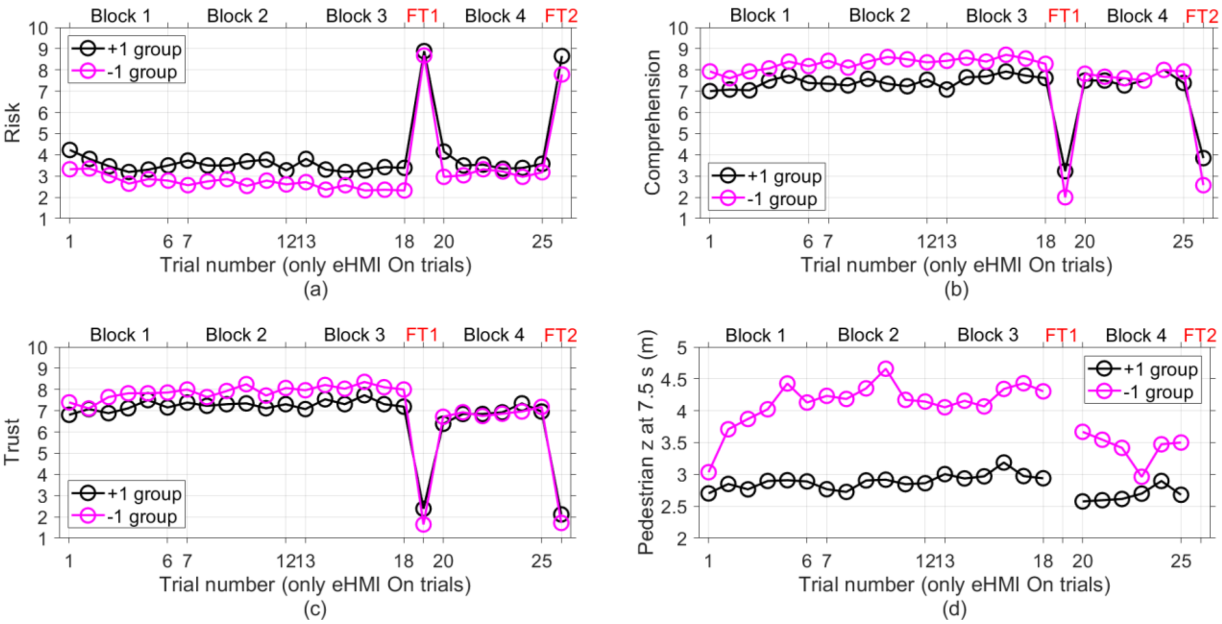

Figure 10. Mean values of (a) perceived risk of the situation, (b) comprehension of the behavior and appearance of the vehicle, and (c) trust in the behavior and appearance of the vehicle, and (d) z-position of the pedestrian at 7.5 s into the trial. The horizontal axis is the trial number (only counting the trials where the eHMI was on). At trial numbers 19 and 26, the eHMI failure occurred. FT1 – Failure trial 1; FT2 – Failure trial 2.

3.3. Comparison between the +1 and -1 groups (eHMI On condition)

Table 3 shows that, for the eHMI On conditions, the perceived risk was generally lower, and the comprehension and trust higher, in the -1 group as compared to the +1 group. However, these differences between the -1 group and the +1 group were mostly small and not statistically significant. A significantly higher comprehension was observed for the '33, On' condition in the -1 group as compared to the +1 group during Blocks 2 and 3. In other words, it seemed that the -1 group, in which the eHMI switched on one second before the vehicle started to decelerate received a higher subjective comprehension than the +1 group, in which the eHMI switched on one second after the vehicle started to decelerate.

We hypothesized that there are earlier crossings in the early eHMI onset (-1 s) group when compared to the later eHMI onset (+1 s) group (H3). This hypothesis was proved from Table 3 and Figure 9 which show that participants in the -1 group walked a further distance in the first three blocks (i.e., before the first failure trial) as compared to participants from the +1 group. Figure 11 shows a boxplot for the average pedestrian z at 7.5 s in Block 3 and 4, respectively ($n = 26$ for the +1 group, and $n = 28$ for the -1 group). An independent *t*-test showed significant differences between the -1 and +1 groups for Blocks 1, 2, and 3 (see Table 3). There were no significant differences between the +1 and -1 group in Block 4, which was after the first failure trial.

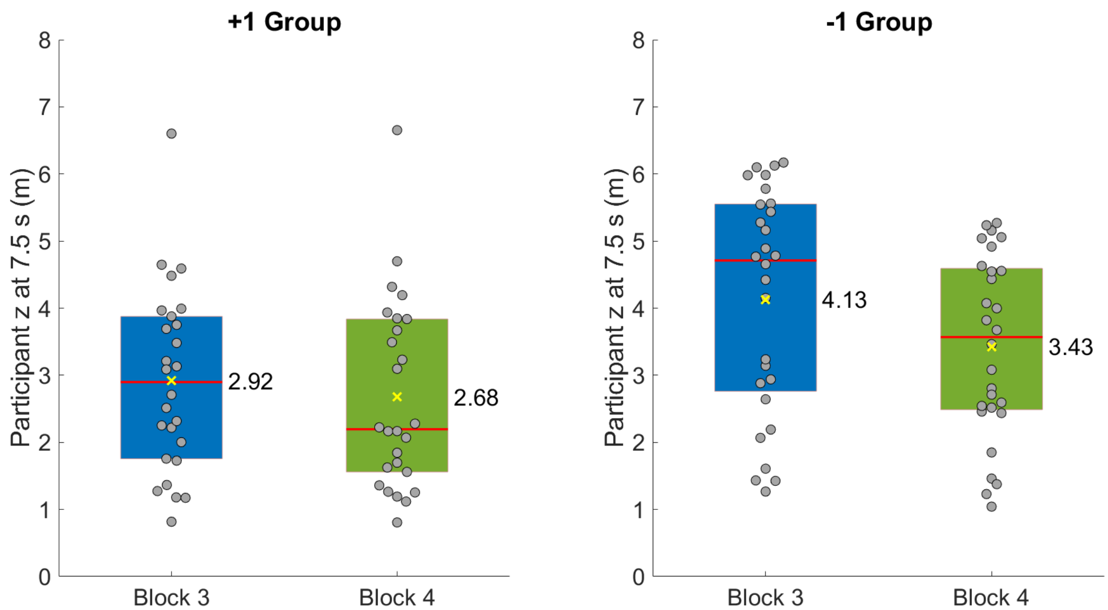

Figure 11. Pedestrian z at 7.5 s in the eHMI On trials of the +1 group and -1 group. The yellow marker 'x' indicates the mean value.

3.4. Percentage of Crashes

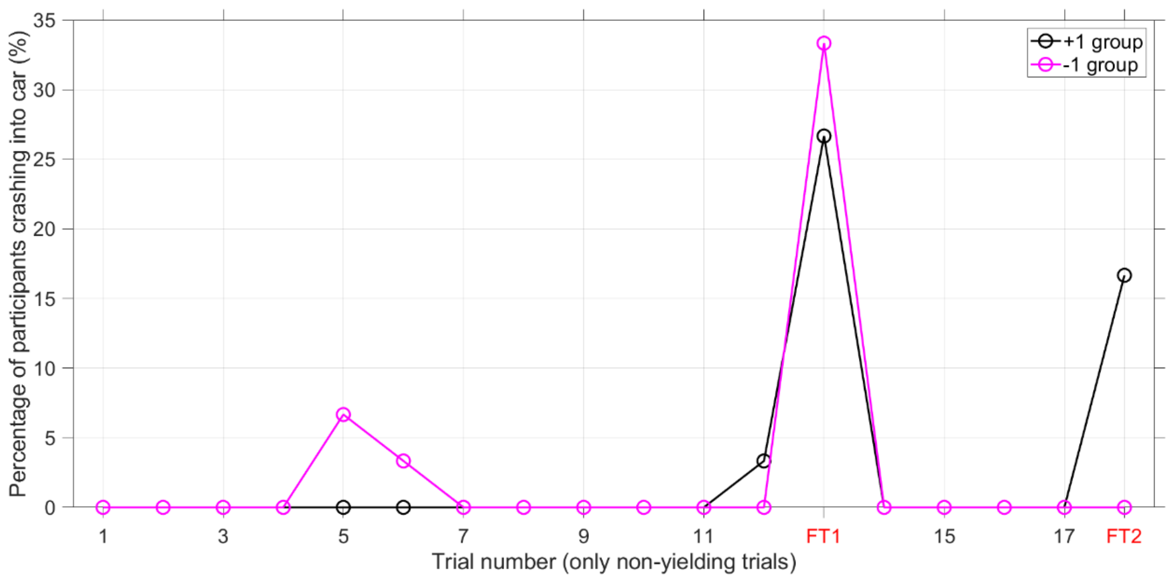

Figure 12. Percentage of participants who crashed with the car during non-yielding trials. FT1 – Failure trial 1; FT2 – Failure trial 2.

From Figure 12, it can be seen that, prior to Failure trial 1, three participants from the -1 group, and one participant from the +1 group walked under the car. About 30 percent of participants from each group walked under the car during the first failure trial. These crashes are consistent with the participants' self-reports described above, showing low trust in the eHMI and AV, low comprehension of the eHMI, and high perceived risk (Table 3 and Figure 10). In the second failure trial, the -1 group yielded no crashes. In the +1 group, five participants who crashed in the first failure trial also crashed with the AV in the second failure trial. We had hypothesized that the later eHMI onset (+1 s) group would yield fewer crashes when compared to the early eHMI onset (-1 s) group (H4). Even though the +1 group yielded fewer crashes in the first failure trial (see Figure 12), a statistical analysis (two-sided Fisher's exact test) indicated that there was no significant variation in the number of crashes between the two groups in both failure trials (FT1: $p = .7773$; FT2: $p = .0208$).

3.5. Questionnaire responses

In the post-experiment questionnaire, participants were asked about what information they used to decide if it was safe to cross. Table 4 shows the number of participants per response option for the question "During the experiment, what information from the vehicle, if any, did you use to decide it was safe to cross?". There was a significant difference in the means between the 'Speed' and 'Distance' information ($t(53) = 4.06$; $p < .001$) and between the 'Speed' and 'eHMI' information ($t(53) = 3.28$, $p = .0018$)

Table 4.
Number of participants per response option according to the increasing importance of each information for the question "During the experiment, what information from the vehicle, if any, did you use to decide it was safe to cross? "

Information	***Unimportant*** *(1)*	***Slightly unimportant*** *(2)*	***Neutral*** *(3)*	***Slightly Important*** *(4)*	***Important*** *(5)*	***Total*** *(100 %)*	***Mean*** *(SD)*
Speed	0	0	3 (5.55 %)	9 (16.67 %)	42 (77.77 %)	54	4.72 (0.56)
Distance	0	4 (7.40 %)	8 (14.81 %)	18 (33.33%)	24 (44.44 %)	54	4.14 (0.94)
Braking	1 (1.88 %)	2 (3.77 %)	2 (3.77 %)	12 (22.64%)	36 (67.92 %)	53	4.50 (0.89)
eHMI(Light band)*	4 (7.40 %)	3 (5.55 %)	4 (7.40 %)	18 (33.33 %)	25 (46.29 %)	54	4.05 (1.20)

*eHMI – External human-machine interface

Table 5 shows the number of participants per response option for the question "To what extent do you think that the usage of this light band actually helps people to comprehend the yielding behavior correctly in real world?". The -1 group received a higher rating than the +1 group. However, this difference was not statistically significant, $t(52) = -2.1738$, $p = .0343$.

Table 5.
Number of participants per response option of rating for the question "To what extent do you think that the usage of this light band actually helps people to comprehend the yielding behavior correctly in real world?"

Group	***Rating***					***Total*** *(100 %)*	***Mean Score***
	1	*2*	*3*	*4*	*5*		
+1 Group	1 (3.84 %)	3 (11.53 %)	5 (19.23 %)	12 (46.15 %)	5 (19.23 %)	26	3.65
-1 Group	0 (0 %)	1 (3.57 %)	1 (3.57 %)	14 (50 %)	12 (42.85 %)	28	4.32

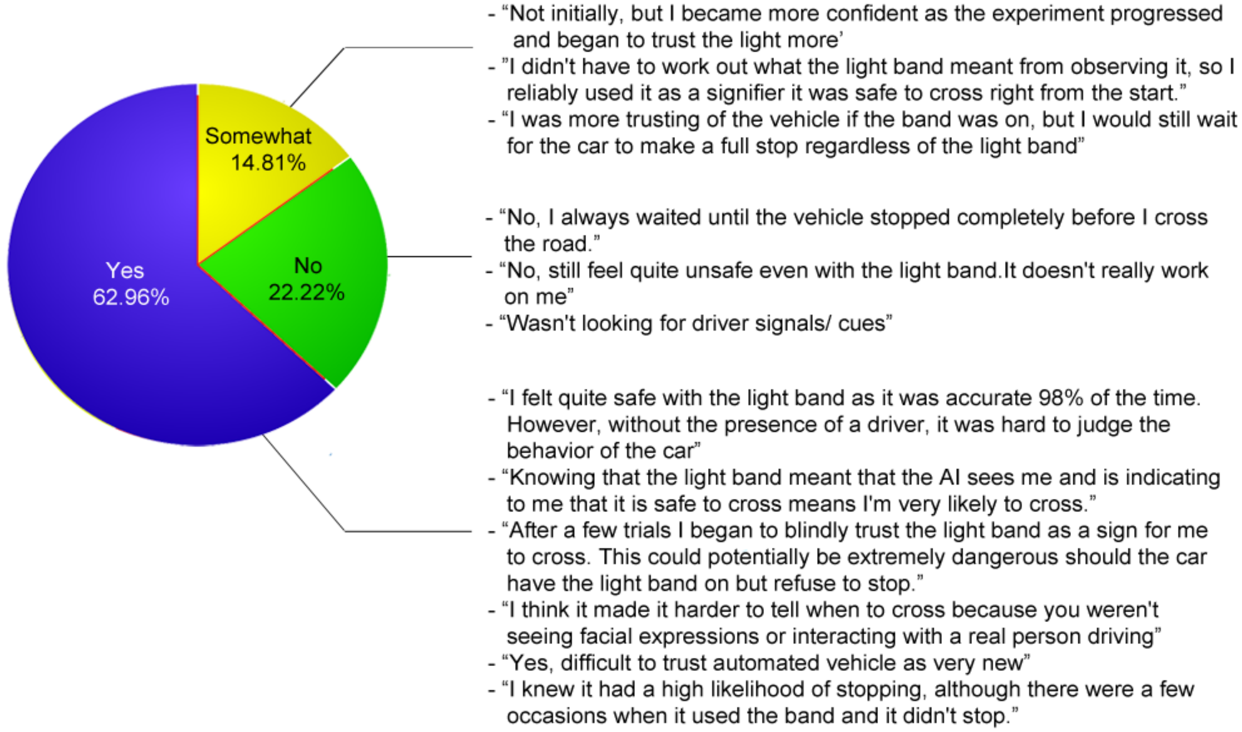

Figure 13. Percentage of participants per response category, who responded to the question "*The vehicle yielded sometimes with the light band ON and sometimes without the light band. Did this difference affect your crossing behavior? If so, then why?"*. The free responses of the participants were categorized manually as 'Yes', 'No', and 'somewhat'. For representation, only some comments are quoted.

Figure 13 and Figure 14 shows that the majority out of 54 participants agreed that their crossing behavior was affected by the eHMI on/off states, and also by the fact that they knew that the car is automated and that the light band meant yielding behavior.

We also asked a question related to the experiment and simulator:
"Do you have any comments on the scenario of the experiment such as realism, daily interactions, speed, external cues, etc.?"
18 out of 54 participants commented on this. Related to the speed, three participants commented that:

- "The speed should not too fast",
- "Speed may be too fast or deceleration not enough. Stopping distance also might be increased", and
- "Speed of the vehicle greatly determines my response".

Eight participants commented on the external cues either relating to the experiment or the real world. Some of the comments were:

- "The light might be confusing when there are multiple cars are involved or on a very sunny day where the sun reflects off the car already.",
- "The false alarm will be really risky in the real-world as people might rely on the sign and started crossing in front of the vehicle. If the car knows the probability of correct yielding maneuver is low it should not project any signal.", and
- "The scenario was ok but the light was actually deceiving. What I looked for was the consequences of my misjudgment".

Concerning the scene, two participants responded that it was very realistic and one participant said that auditory aspects could be added to the virtual reality.

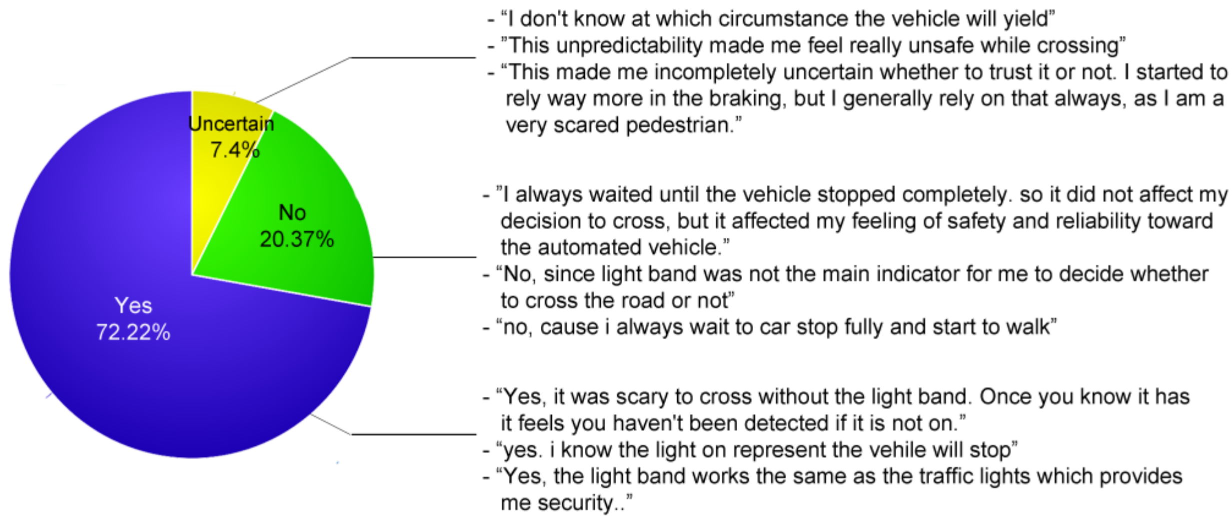

Figure 14. Percentage of participants per response category, who responded to the question "*Did the fact that you already know that the vehicle is automated and the information that the light band actually means yielding behavior affect your crossing decision and behavior? If so, then how?*". The free responses of the participants were categorized manually as 'Yes', 'No', and 'uncertain'. For representation, only some comments are quoted

Presence Questionnaire. The presence questionnaire consisted of 20 questions. Table 6 shows the means and standard deviations of responses to 20 questions from the presence questionnaire involving the sense of movement in the simulator, control of events, and interaction with the virtual environment. The mean scores in Table 6 indicate that participants could move and interact with the virtual environment effectively, and were more involved in and also adjusted to the virtual environment experience quickly, and felt a high sense of moving inside the virtual environment. The experiment did not have any sound which is why participants provided very low scores for the question about the auditory aspects.

In the end, all participants were given an opportunity to comment on their experience with the CAVE virtual environment out of which only 8 had commented. Some example comments were:

- "It was really fun",
- "It was interesting and it kept with the realism of crossing roads in real life", and
- "The sound system could improve the experience and fidelity of the simulation."

Table 6.
Mean and SD of scores of responses from the presence questionnaire

	Question	Mean	SD
1	How proficient in moving and interacting with the virtual environment did you feel at the end of the experience? (1 - Not Proficient; 7 – Very proficient)	6.44	0.66
2	How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities? (1 – Not at all; 7 – Completely)	6.20	1.05
3	How closely were you able to examine objects? (1 – Not at all; 7 – Very closely)	5.57	1.36
4	How much did the auditory aspects of the environment involve you? (1 - Not at all; 7 – Completely')	3.09	2.17
5	How quickly did you adjust to the virtual environment experience? (1 - Not at all; 7 – Less than one minute)	6.16	0.94
6	How natural was the mechanism which controlled movement through the environment? (1 - Extremely artificial; 7 – Completely natural)	5.85	1.07
7	Were you able to anticipate what would happen next in response to the actions that you performed? (1 – Not at all; 7 – Completely)	5.50	1.35
8	How responsive was the environment to actions that you initiated (or performed)? (1 – Not responsive; 7 - Completely responsive)	5.81	1.18
9	How involved were you in the virtual environment experience? (1 - Not involved; 7 - Completely engrossed)	6.05	0.89
10	How natural did your interactions with the environment seem? (1 - Extremely artificial; 7- Completely natural)	5.74	1.38
11	How compelling was your sense of objects moving through space? (1 – Not at all; 7 – Very compelling)	6.14	0.93
12	How much did the visual aspects of the environment involve you? (1 – Not at all; 7 – Completely)	5.61	1.20
13	How much delay did you experience between your actions and expected outcomes? ((1 – No delays; 7 – Long delays)	2.33	1.55
14	How much did your experiences in the virtual environment seem consistent with your real world experiences? (1 – Not consistent; 7 – Very consistent)	5.53	1.22
15	How completely were you able to actively survey or search the environment using vision? (1 – Not at all; 7 – Completely)	6.01	1.01
16	How much did the control devices/ motion sensors interfere with the performance of assigned tasks or with other activities? (1 – Not at all; 7 – Interfered greatly)	2.50	1.69
17	How well could you examine objects from multiple viewpoints? (1 – Not at all; 7 – Extensively)	5.37	1.30
18	How compelling was your sense of moving around inside the virtual environment? (1 – Not compelling; 7 – Very compelling)	6.07	1.04
19	How much did the visual display quality interfere or distract you from performing assigned tasks or required activities? (1 – Not at all; 7 – Required task performance)	2.01	1.07
20	How much were you able to control events? (1 – Not at all; 7 – Completely)	4.44	1.73

4. DISCUSSION

With automation progressing at an unprecedented rate in recent years, it is important to identify the limitations of automation and the ways these limitations can be overcome. The objective of our study was to investigate pedestrians' trust and misuse of an AV equipped with an eHMI. It was hypothesized that participants' trust would drop to a low level when the eHMI fails (*H1*) followed by a sustained loss of trust in the correct functioning of the eHMI after experiencing the failure (*H2*). Furthermore, misuse of the eHMI was expected, operationalized as a situation where participants who were exposed to the eHMI signal before the AV began to decelerate (-1 group), would start to use the information from the eHMI and start crossing early instead of relying on the implicit communication from the vehicle (*H3*). Finally, it was expected that participants who were exposed to the eHMI signals after the AV began to decelerate (+1 group) would be run over by the AV less often when the eHMI fails as compared to participants in the -1 group (*H4*).

4.1. Main findings:

4.1.1. Trust dynamics

In post-trial questions, participants stated the perceived risk of the situation they experienced, followed by how much they comprehended the approaching vehicles' behavior, and followed by the trust they had in the automated vehicle system.

Results showed that participants trusted the AV more with the eHMI on when compared to the AV without eHMI. These results are in line with Faas et al. (2020), who showed that pedestrians exhibited higher trust in self-driving cars with an eHMI than without an eHMI. Also, the risk was lower and comprehension higher when the eHMI was on compared to no eHMI. However, when failure had occurred in the eHMI, their trust in both the eHMI and the AV was considerably reduced (see Figure 10) confirming hypothesis *H1*. This hypothesis also supports the results of Holländer et al. (2019) and of Lee and Moray (1992), who found that when participants experience a failure in the automated system (or eHMI), their trust declined strongly. It is surprising that without prior experience with AVs or eHMIs, the participants rated a high initial trust in the first three blocks of the experiment. Thus, consistent with Parasuraman and Riley (1997), participants showed inappropriate reliance on the automation (i.e., improper calibration of their trust in the automation system).

As expected (*H2*), the failure in the eHMI led to a loss of trust after Block 3; this loss of trust was especially significant for the -1 group, who experienced the eHMI onset before implicit communication from the AV. This loss of trust in Block 4 for the -1 group may have caused disuse of the eHMI. It is possible that, after having experienced a failed eHMI, the -1 group started crossing by relying more prominently on the implicit communication of the AV to confirm the lightband signal.

4.1.2. Reliance on eHMI for crossing

The obtained results and the above-discussed effects were investigated with two different eHMI onset timings (-1 s and +1 s). The results revealed that the participants felt less risky when they encountered the AV with the eHMI on when compared to the eHMI off (see Table 3), which is in line with Faas et al. (2020), who showed that participants felt safer and trusted the AV more with the eHMI than without an eHMI. Additionally, the results of De clercq et al. (2019) showed that participants felt significantly safer to cross when the AV is equipped with an eHMI and also were most likely to press the button when the eHMI turned on earlier before the AV started decelerating which indicated an earlier crossing intention. Our study also showed a similar effect where the -1 group relied on the eHMI more and moved further to the road if the eHMI was on before the AV started decelerating as compared to the +1 group where the eHMI turned on after the vehicle started decelerating. These effects are evident from Table 3, Figure 9, Figure 10, and Figure 11, thereby proving hypothesis *H3*.

We evaluated the number of participants getting run over by the AV in non-yielding trials as an index of misuse of the eHMI. Thus, we aimed to verify whether participants misused the eHMI during failure trials (*H4*). Even though a single crash when an eHMI failed is fatal and not acceptable, we wanted to examine if the participants in the +1 group relied less on the eHMI than the -1 group. Here, we expected that the +1 group would yield fewer crashes than the -1 group when the eHMI fails. Interestingly, the results revealed that a substantial proportion (~30%) of participants from both onset-timing groups crashed with the AV in Failure Trial 1 (see Figure 12). More specifically, the +1 group had participants crash in both failure trials, which was contrary to the formulated hypothesis *H4*. We can speculate that the participants in the -1 group, especially those who had crashed in Failure Trial 1, learned that the anticipatory signals cannot be trusted and relied upon. This learning experience of the -1 group in Failure Trial 1 could have made them more aware of the functioning of the eHMI in Block 4 and could also be the reason why nobody in the -1 group crashed in failure trial 2. This speculation is also supported by Figure 11, which showed that the participants in the -1 group walked less far towards the road in Block 4 when compared to Block 3 demonstrating possible disuse of the eHMI. Furthermore, both groups showed a similar decline of trust when the eHMI failed again (Failure Trial 2) (see Figure 10). All the above-discussed facts and possibilities could be the reason why there was no significant evidence that the groups differ in the number of crashes in both failure trials, thus not rejecting hypothesis *H4*.

4.2. Pros and cons in our study

Pros:

- The study was conducted in a CAVE simulator. Participants were able to move freely around the simulator and could also see their own body in the environment which is not possible in most simulators that use VR headsets. This is a likely explanation for their higher ratings in the proficiency in moving and interacting in the simulator which also had a significantly positive correlation with how natural they felt in interacting with the simulation environment (see Table 12 in Appendix J).
- We did not use a handheld device to trigger trials of the experiment. Instead, to trigger a trial the participants interacted hands-free with trigger colliders programmed in the virtual environment.
- We used high-end processors to minimize visual delays in the experiment. The high-end hardware may explain the fact that in the presence questionnaire Q13, the delay was rated as only 2.33 on a scale of 1 to 7. The low delay could also be a reason why none of the participants reported any simulation sickness except for one participant who verbally commented that she felt slightly dizzy with walking back and forth for crossing.
- As the HIKER is the largest known CAVE simulator, the simulator floor was spacious (36 square meters), which enabled the participants to cross the virtual road similar to real-world crossings and without any obstructions.

Cons:

- The simulator did not include a surround sound system. Adding sounds may "improve the experience and fidelity of the simulation", as commented by one participant.
- Apart from the participants' comments in the questionnaires, some verbally commented that they found the resolution and the quality not too high. This is partially because the tint in the stereo glasses added to the reduced color perception and also the stereo simulation could be only run at a slightly reduced resolution than the achievable 4K resolution by all eight projectors.

4.3. Recommendations for future research

Some recommendations for future studies relating to the simulator and the virtual environment are as below:

- Our study involved only one AV in a single lane and just the participant acting as a pedestrian. It is recommended that future studies use a heterogeneous mixture of traffic with multiple cars and multiple pedestrians attempting to cross. This could improve a naturalistic data collection in the research.
- We designed the game scene for a typical UK street. A design with a naturalistic city environment with tall buildings and traffic lights could also be studied and compared, such as low traffic environment vs. high traffic environment crossing.
- We evaluated the trust in the eHMI during a bright sunny day. It is recommended to also study the trust and crossing behavior of pedestrians with the eHMI in varying weather conditions and daytimes.
- Our simulator can already track the position of the participant and their head rotation. Additionally, using body trackers could help in evaluating the crossing behavior of the participants in much detail.

Here, we put forth some recommendations which might help to overcome overtrust and misuse in future eHMI designs:

- Results showed that irrespective of the eHMI onset timings, participants crashed with the AV. It is recommended to do an intensive study about pedestrians' trust and whether the pedestrians base their crossing decisions on the implicit communication of the AV or the signals from the eHMI. Such a study could help in an appropriate design for the safe behavior of eHMI in the future.
- Currently, various eHMI concepts are being researched and tested in self-driving cars. Keeping in mind critical factors such as cultural differences, pedestrians' perception of the eHMI, and type of information the eHMI provides (vehicle-centric or pedestrian-centric), the automotive industry should standardize the eHMI design. Standardization can help the pedestrians to avoid any possible confusion or misinterpretation which can occur when interacting with multiple eHMI designs.
- Pedestrians should be made aware of the capabilities of the automated driving system and that it can fail to detect a pedestrian anytime pertaining to various environmental and traffic factors and also that the automation is prone to malfunction, for example, the eHMI turns on mistakenly when the AV detects a pedestrian but does not have an intention to yield for the pedestrian. Training/education could help pedestrians maintain a calibrated amount of trust and could prevent misuse/disuse of the automated driving system.

5. CONCLUSION

From the results of this study, it can be concluded that pedestrians are prone to misusing an eHMI after repeated exposure to that eHMI. The eHMI onset timing does not appear to cause much difference when it comes to misusing the eHMI. When an eHMI signals the intent of the AV before the actual intent communication of the AV, it makes the pedestrians cross earlier when compared to an eHMI that turns on after the vehicle starts to decelerate.

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Appendix A:
Figures from literature

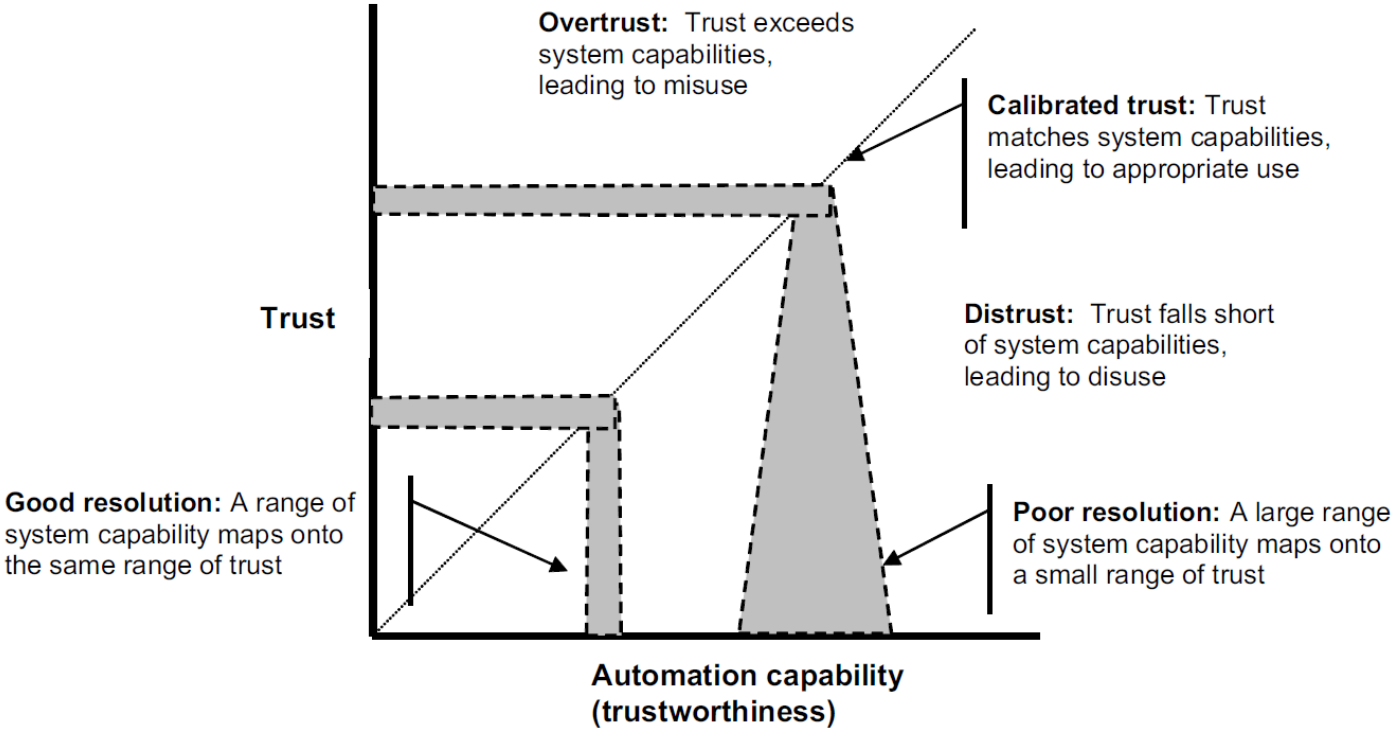


Figure 15. The relationship between calibration, resolution, and automation capability in defining appropriate trust in automation. Overtrust may lead to misuse and distrust may lead to disuse. (Copied from Lee and See, 2004)

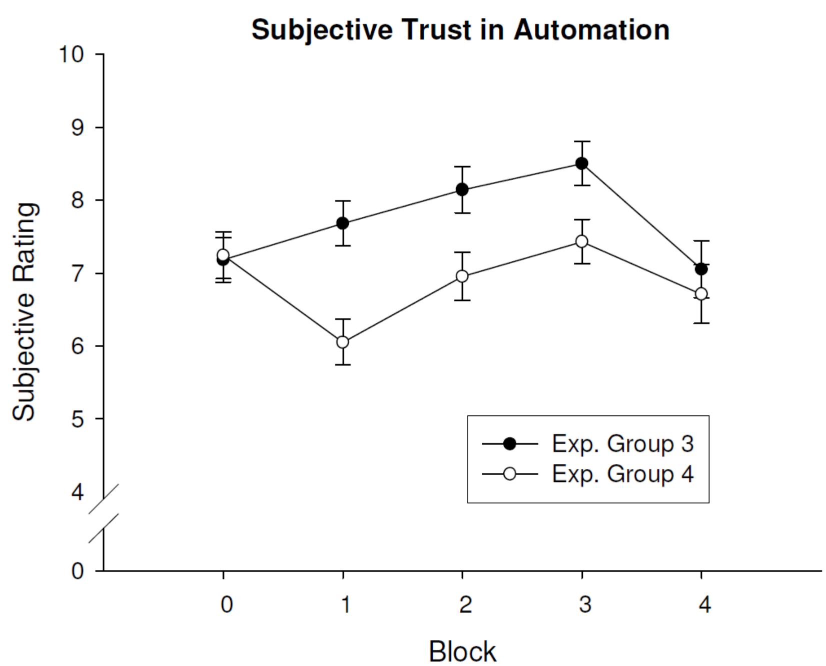


Figure 16. Time course of subjective trust ratings across experimental blocks for participants of experimental groups #3 and #4 (block 0 = subjective trust rating after training with the aid) (Copied from Reichenbach et al.,2012)

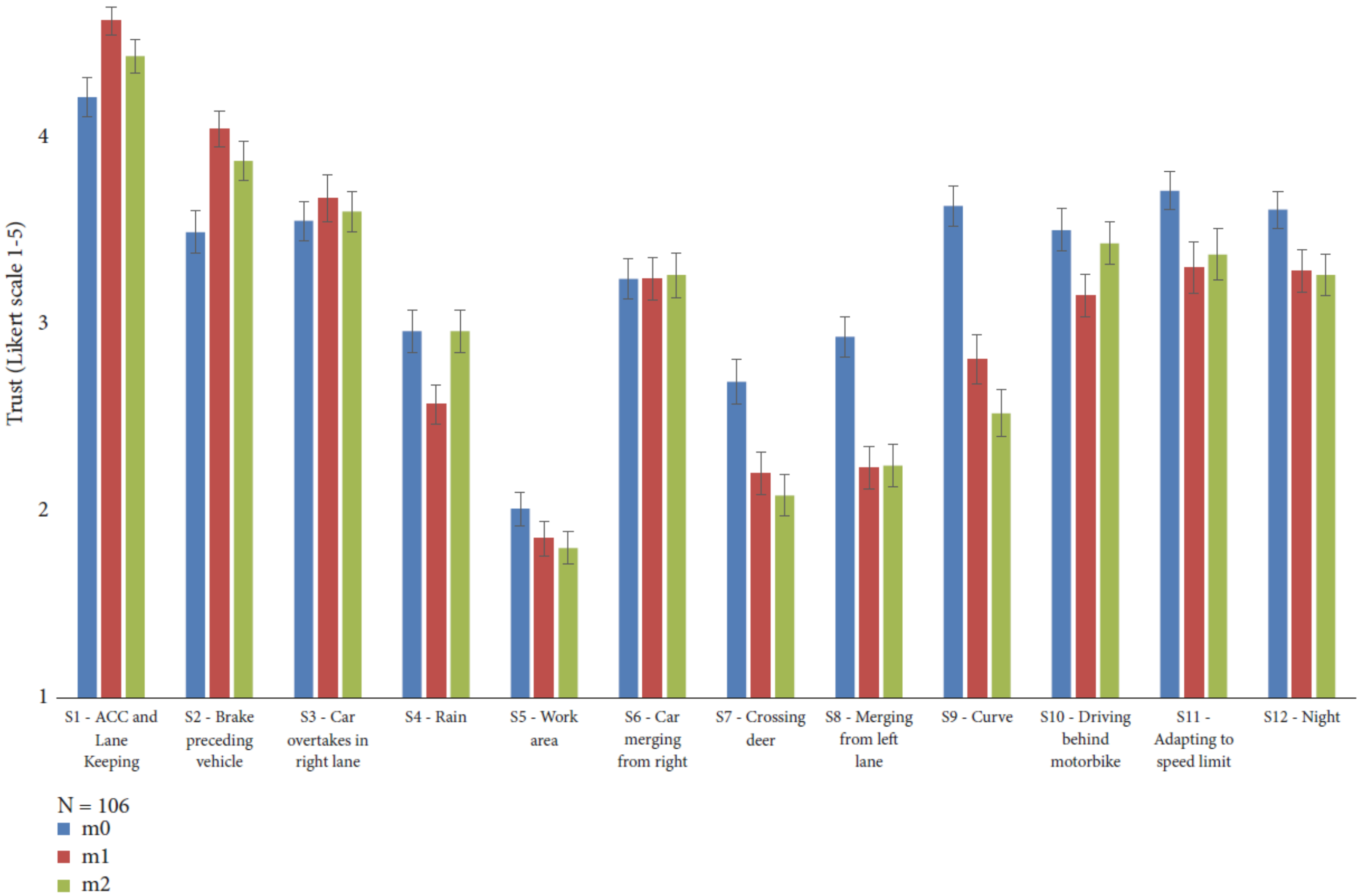


Figure 17. Questionnaire results. Scenarios (S) one to twelve are displayed from left to right, respectively. For scenarios 1 and 2, drivers' trust significantly increased after experiencing the vehicles. Conversely, for scenarios 4, 7, 8, 9, and 12, drivers' trust significantly decreased after experiencing the vehicles. No significant trust changes between pre- and post-measurements were found for scenarios 3, 5, 6, and 11. For scenario 10, significant differences were found between the pre- and the "2-week" measurement (i.e., m2), but not between m0 and m1. α =.004. (Walker et al., 2018)

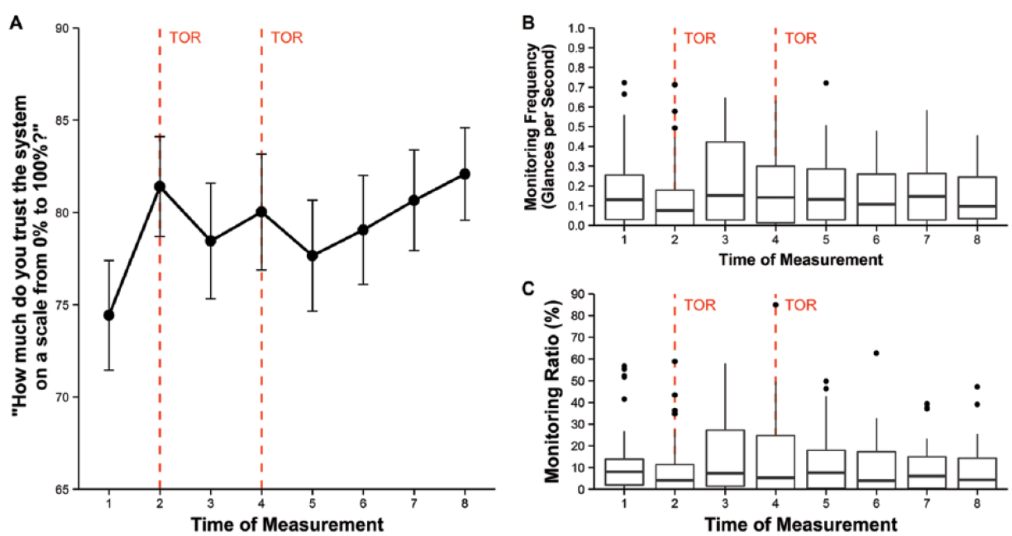


Figure 18. Mean self-reported automation trust (A, showing standard errors bars), median monitoring frequency (B), and median monitoring ratio (C) during non-driving-related tasks. (Hergeth et al., 2016)

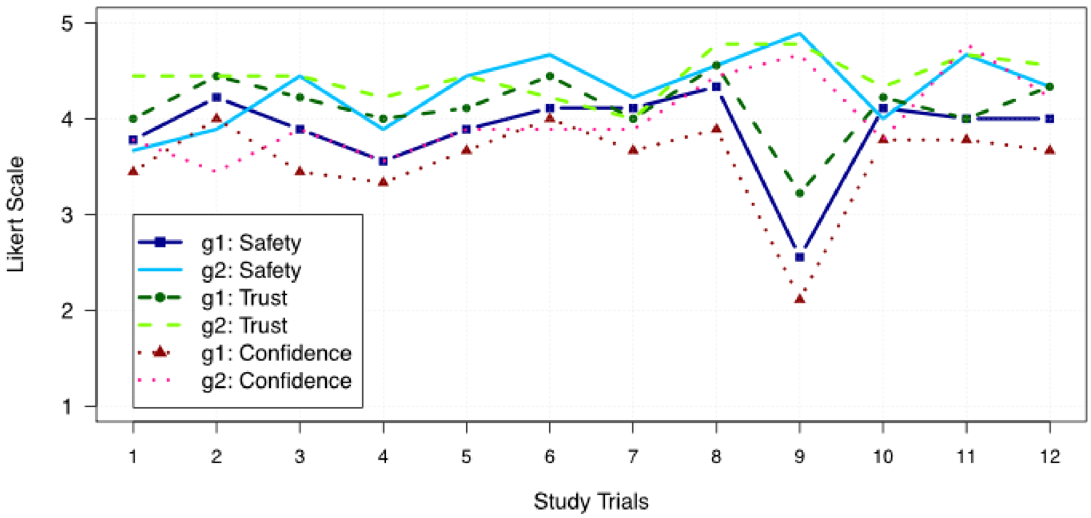


Figure 19. Mean values for perceived safety while crossing, trust in the externals display and confidence in the AV for both groups (g1: mismatching AV signals; g2: matching signals). Trials are on the horizontal axis, Likert scale values on the vertical. In the ninth trial a mismatch in displayed information occurred for participants of group 1 (Copied from Holländer et al., 2019)

Appendix B:

HIKER (Highly Immersive Kinematic Experimental Research) Lab

The HIKER

The Highly Immersive Kinematic Experimental Research (HIKER) lab is the largest, 'CAVE-based' pedestrian simulation environment of its type in the world. The HIKER lab allows participants to interact with a variety of urban environments and vehicles in a 9 x 4 m walking space with a level of real-world performance that is not possible using head-mounted Virtual Reality equipment.

The walls of the HIKER lab are plate glass with rear projection from an array of 4k projectors, with the whole scene responding to the participants head position and gaze. The result reproduces VR without the need for research participants wearing a VR headset, the use of which might undermine experiments that need to capture fine movements in real time. A notable example of this is the need for accurate split-second measurement of the interaction of people and vehicles in life-threatening situations. Safe pedestrian interaction with Autonomous Vehicles is a key current example of the research contribution of the HIKER lab

Physical setup:

The HIKER lab is enclosed in a room of 8 x 14 x 7m approx. This room contains the full structure to hold the projectors, screens, and the rack of computers that power the CAVE System.

The CAVE space is formed by a setup of 3 glass panels (4 x 2.5m for the front and 9x2.5m for the lateral screens) and a wooden floor (9 x 4m) that act as screens for the projection system.

Attached to the structure that keeps the screens in place are the projectors that will rear-project the images onto these, as well as one projector above the whole structure to provide the floor projection.

Hardware:

For being able to run the cave system, the facility counts with a rack of 9 computers. One for general management and development, and a dedicated one for each projector. All these are attached to a KVM switch to facilitate general management.

- All 9 computers are identical and have the following main specifications:
    - Intel® Core™ i9-7900X CPU @ 3.30GHz
    - 128 GB Ram DDR4
    - NIVIDA Quadro P4000 8GB GPU

- The projectors are 8 Barco F90 4k projectors projecting at 120Hz (https://www.barco.com/en/product/f90-4k13)
- The head and controller tracking is made by a set of 10 VICON Vero v2.2 (2.2MP). See picture below

F90-4K13 - Barco

The image quality and laser phosphor light source of Barco's F90 projectors enable you to provide exceptional experiences while saving both time and money.

www.barco.com

Software:

Each of the machines runs under Windows 10.

The tracking and VRPN server are done using VICON Tracker 3.7.   Currently it tracks two pairs of different glasses. Active stereo glasses, (tracked object name “Glasses”) and mono glasses, (tracked object name “MonoGlasses”). Also, a Vicon Apex device used for user control and interaction.

Model	v2.2
Resolution (MP)	2.2 (2048 x 1088)
Max Frame Rate (Hz)	330 @ 2.2MP
Max Frame Rate (Hz)	330
On-Board Marker Processing	-
Standard Lens	6-12 mm Varifocal
Wide Lens	6-12 mm Varifocal
Minimum Standard FOV (H x V)°	44.1 x 23.6 (tele)
Minimum Wide FOV (H x V)°	98.1 x 50.1 (wide)
Camera Latency	3.6 ms
Strobe	IR
Shutter Type	Global
Connection Type	Cat5e / RJ45
Power	
Max Power Consumption	
Dimensions (mm) (H x W x D)	83 x 80 x 135
Weight (Kg)	0.57
Updateable Firmware	Yes

Figure 20. Outside view of ‘Virtuocity’ where the HIKER is located

Figure 21. Entrance to the HIKER Lab

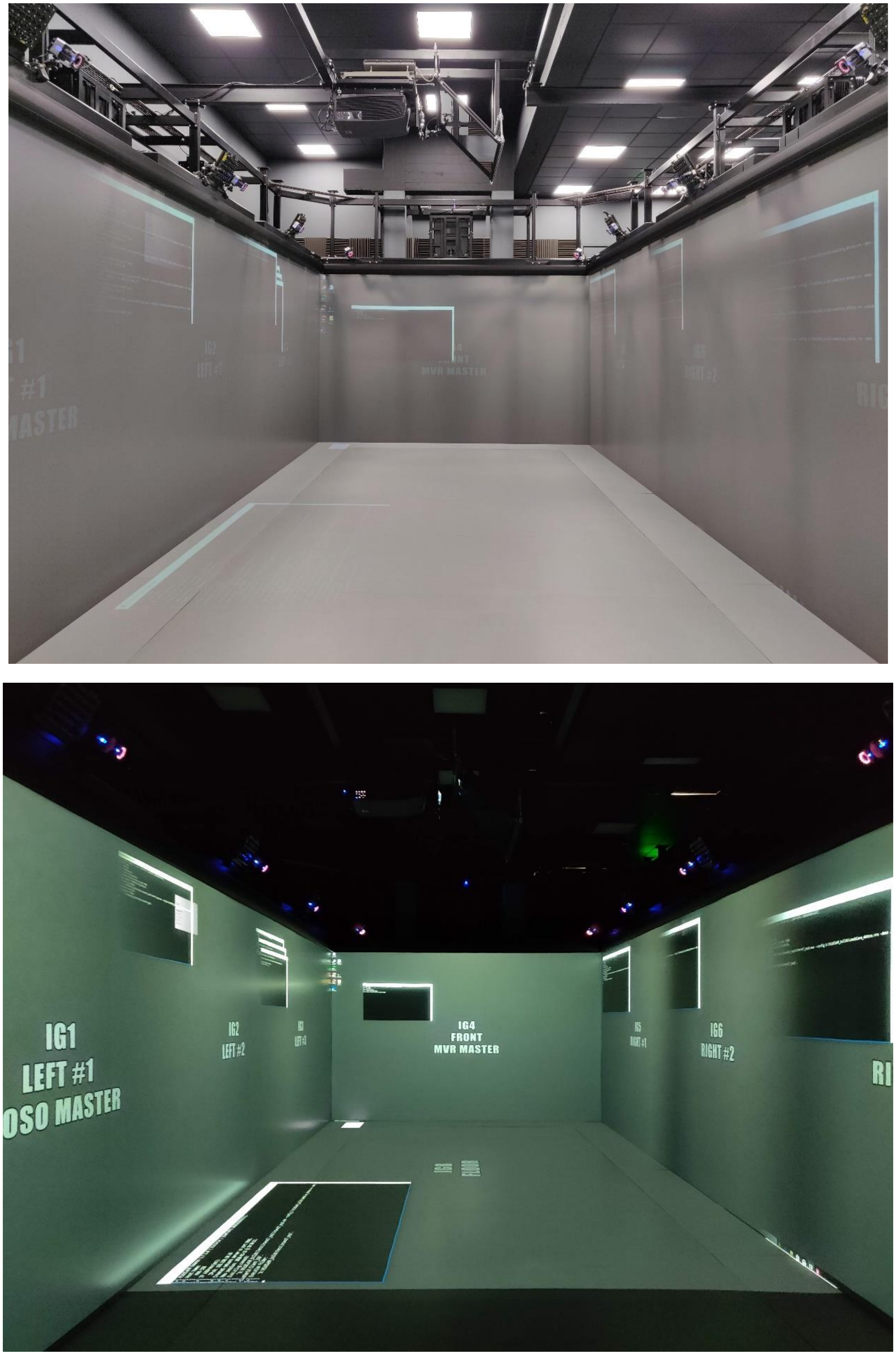


Figure 22. The HIKER pedestrian simulator which is 9m x 4m; Top: With lights on, Bottom: With lights off

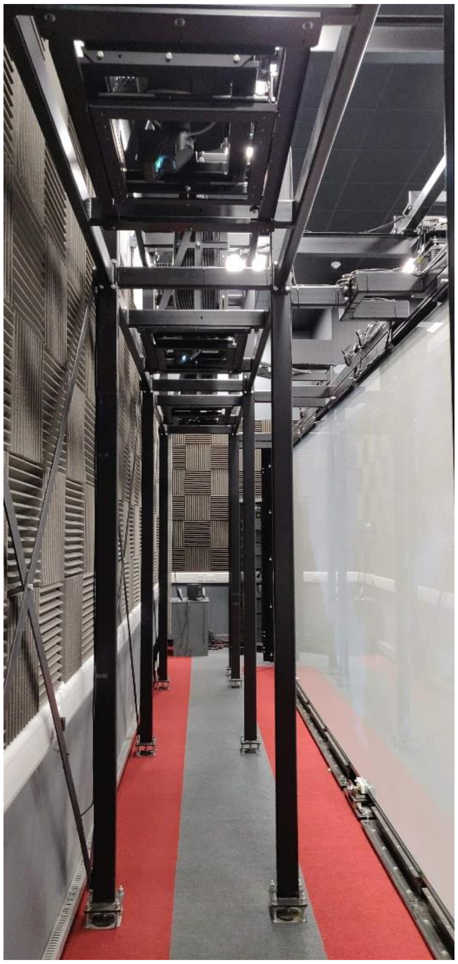


Figure 23. The left side of the HIKER where the projectors are fitted on a metal frame

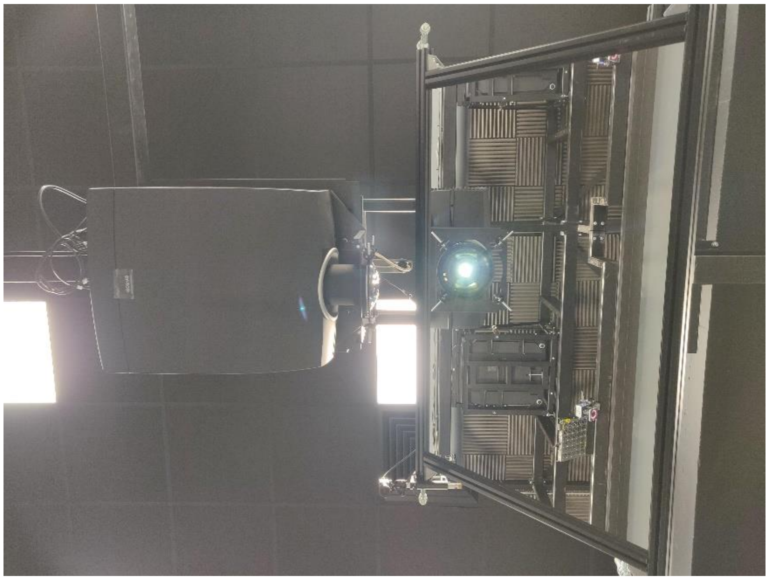


Figure 24. The projector on top for ground projection in the HIKER

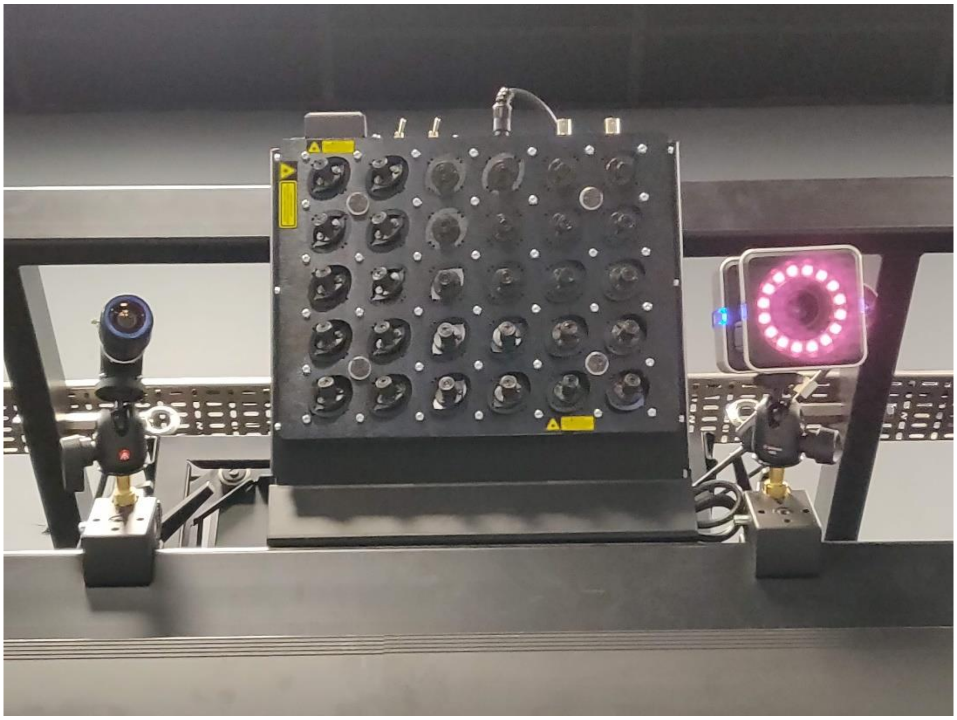


Figure 25. The motion cameras and IR sensors for the motion tracking of the participant

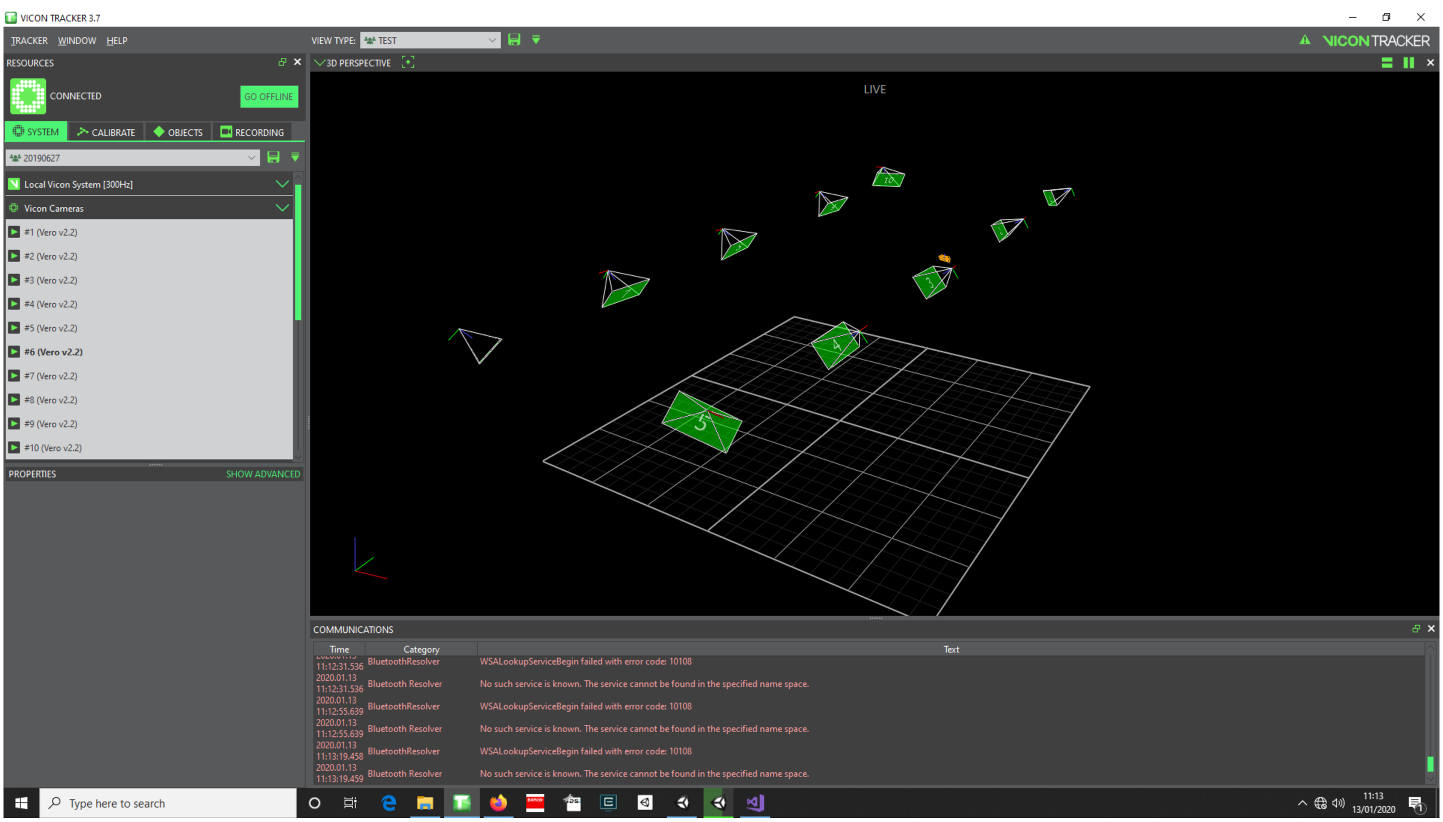


Figure 26. A screenshot of the Vicon tracker software showing the setup of the motion trackers. This makes sure that the motion cameras are working properly and also to reset and calibrate cameras and trackers in case of any fault

Figure 27. The computer network connected to one Host computer and eight projectors

Figure 28. The HIKER lab in charge working on the simulation Host PC

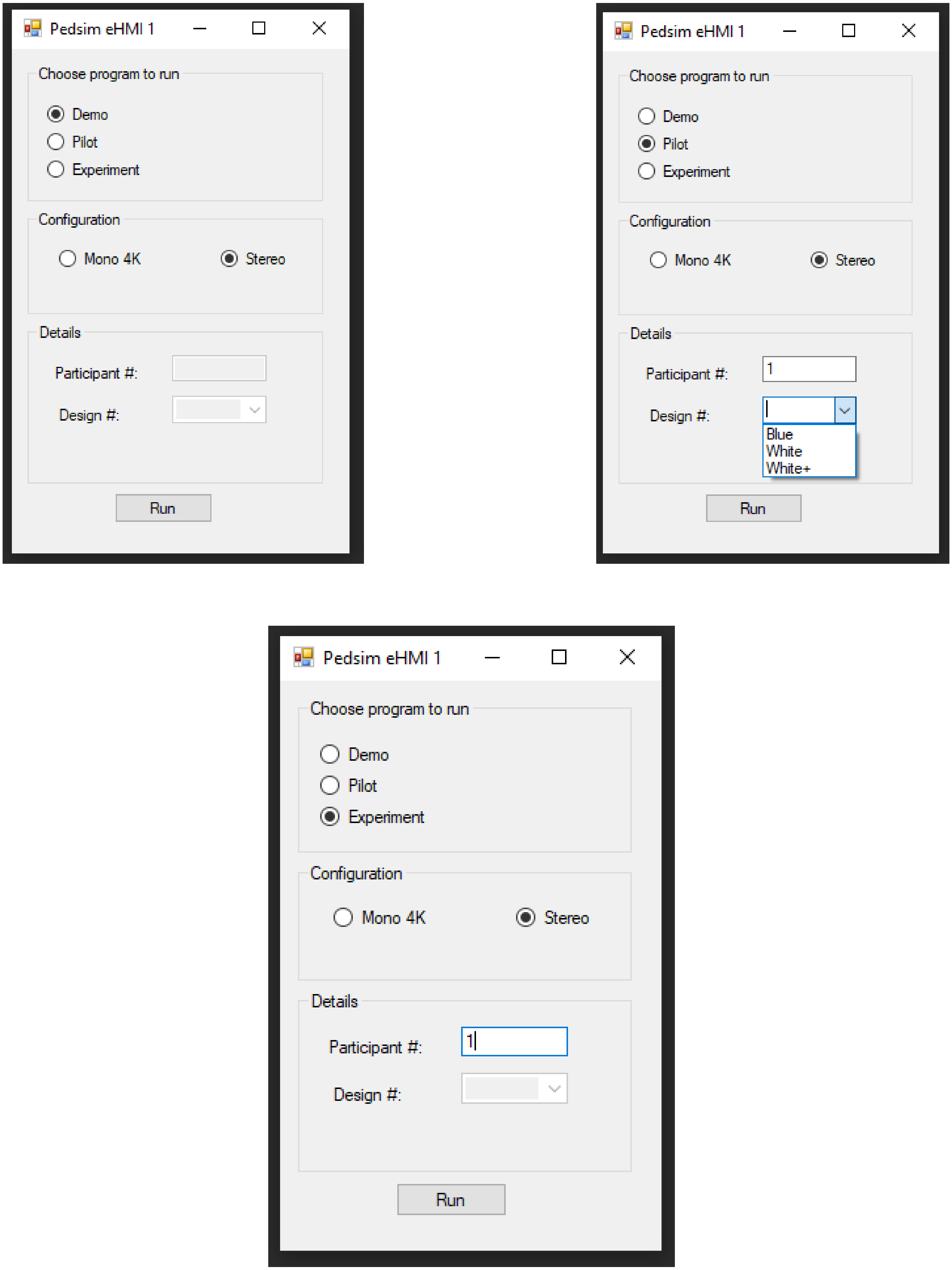
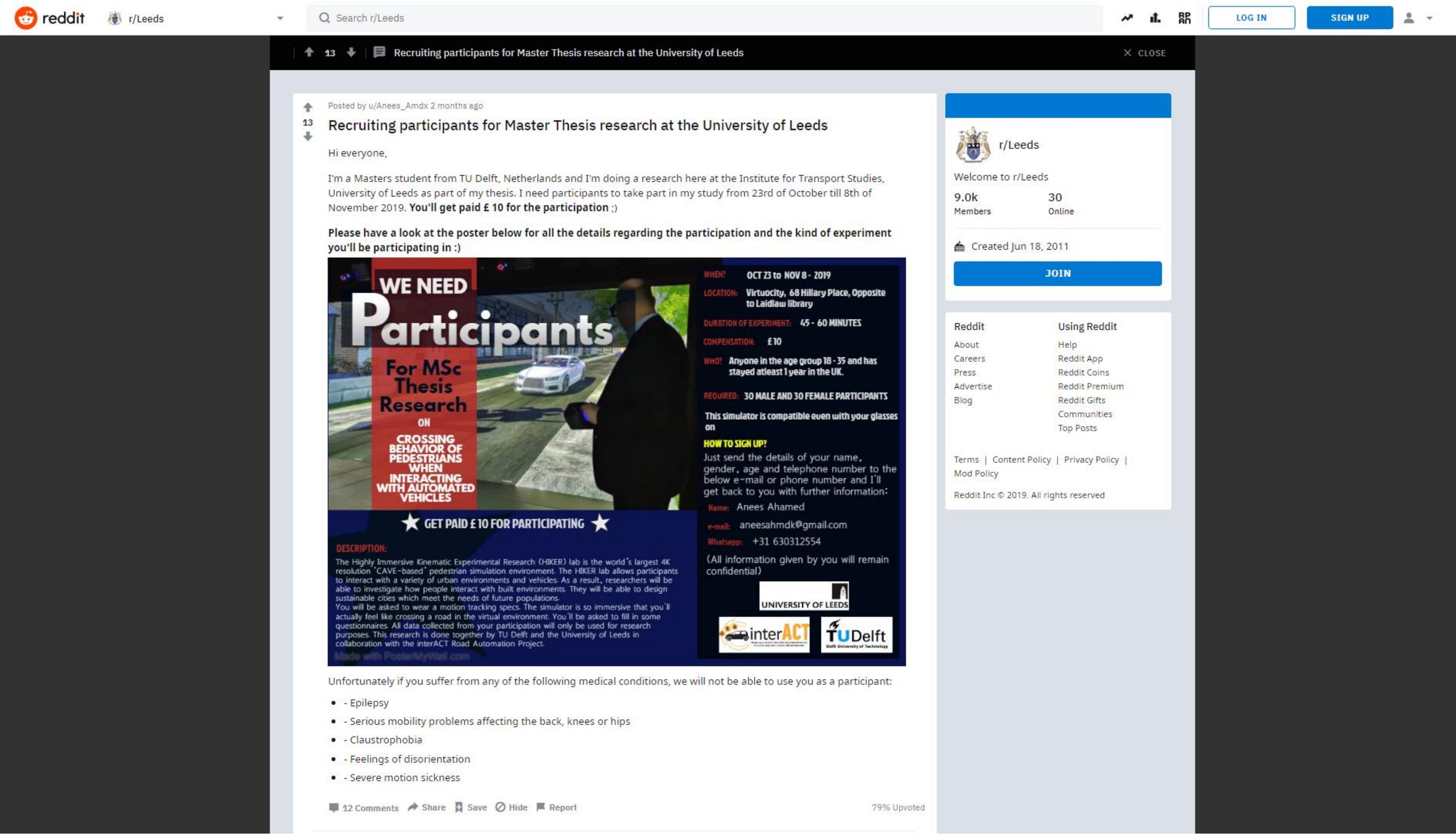


Figure 29. Screenshots of the executable application window. The UI shows how the demo, pilot, and the main experiment is run accordingly

Appendix C:
Participant Recruitment

Recruitment Poster:

Social network recruitment:



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13 Recruiting participants for Master Thesis research at the University of Leeds CLOSE

Posted by u/Anees_Amdx 2 months ago

13

Recruiting participants for Master Thesis research at the University of Leeds

Hi everyone,

I'm a Masters student from TU Delft, Netherlands and I'm doing a research here at the Institute for Transport Studies, University of Leeds as part of my thesis. I need participants to take part in my study from 23rd of October till 8th of November 2019. **You'll get paid £ 10 for the participation** ;)

Please have a look at the poster below for all the details regarding the participation and the kind of experiment you'll be participating in :)

Unfortunately if you suffer from any of the following medical conditions, we will not be able to use you as a participant:

- - Epilepsy
- - Serious mobility problems affecting the back, knees or hips
- - Claustrophobia
- - Feelings of disorientation
- - Severe motion sickness

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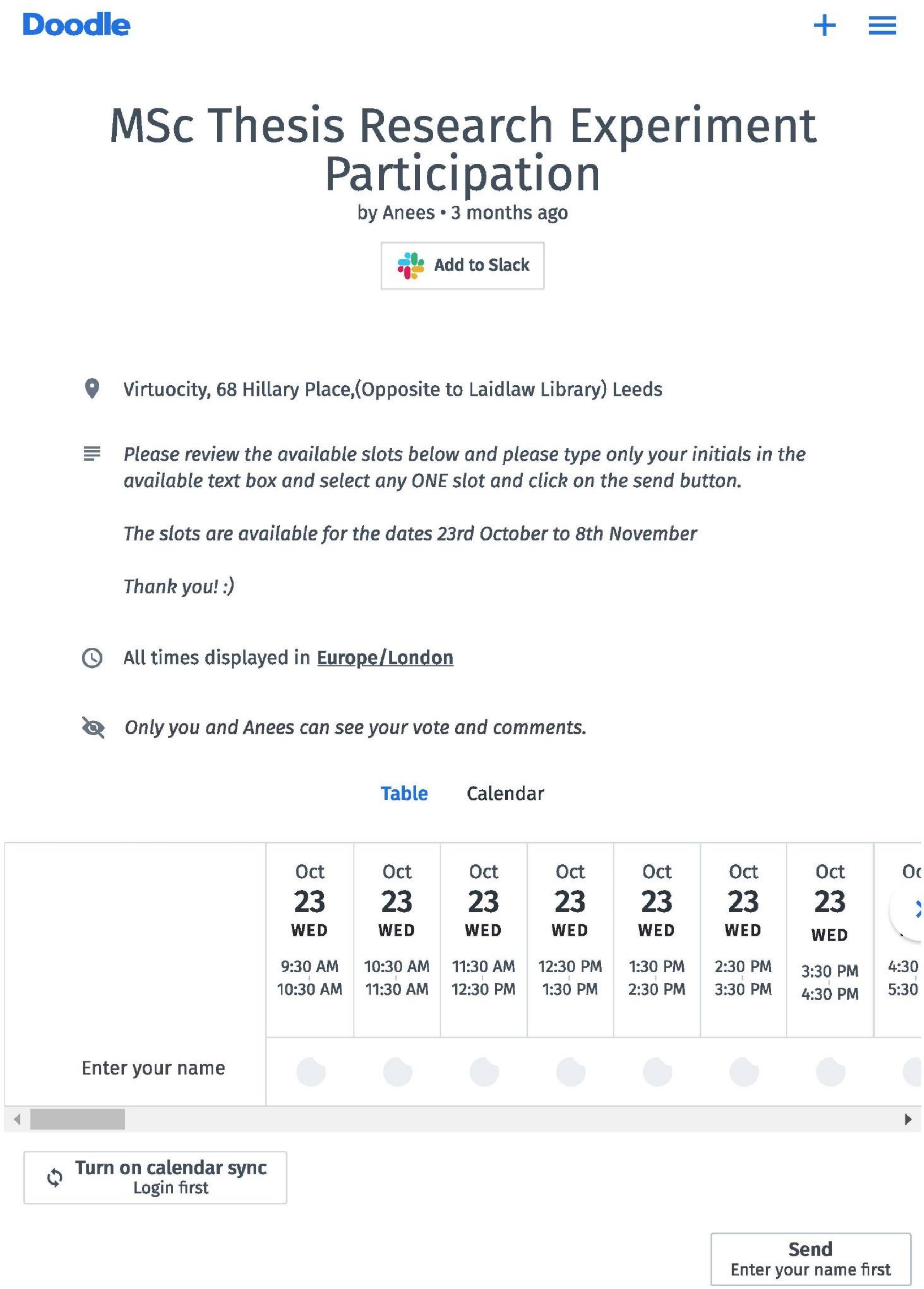
Participant slot selection:



Appendix D – Pilot Study

Three participants participated in the pilot study. The aim for the pilot study was to assess the simulator settings and also to finalize the eHMI design for the main study. We evaluated three eHMI designs: (1) 360° Blue light band, (2) 360° White light band, (3) 360° and front grill wider and bright white light band. From the pedestrian responses, the participants rated the '360° and front grill wider and bright white light band' eHMI design to be most interactive, visible, and predictive.

Pre-Experiment Questionnaire

Thank you for agreeing to participate. Please bear some patience in filling out this questionnaire before we start with the experiment. This shouldn't take more than 3 minutes.

* Required

1. **Participant Number (We know it. So you needn't worry about this)** *

____

2 **What's your age?** *

____

3. **What's your gender?** *
   Mark only one oval.

   - Male
   - Female
   - Prefer not to say
   - Other: ______________________________

4. **What's your Nationality?** *

____

5. **How often do you walk outside in an average day?**
   Mark only one oval.

   - Never
   - Rarely (0 - 2 times a day)
   - Often (2 - 4 times a day)
   - Frequently (4+ times a day)

6. **What time range best describes your daily walking time?** *
   Mark only one oval.

   - 0 -15 minutes
   - 15 - 30 minutes
   - 30 - 45 minutes
   - 45 - 60 minutes
   - > 60 minutes

7. **What is the main reason for your walking trips?**
Mark only one oval.

- Commuting
- Leisure
- Other

8. **How long have you been living in the UK?** *
Mark only one oval.

- Since birth
- Moved in a few years ago
- Student (< 3 years)

9 **Do you possess a drivers' licence? If Yes, specify the year you got it.** *

____

10. **How often do you drive in a month?** *
Mark only one oval.

- Every day
- Just Weekdays
- Just weekends
- Once per week
- Only once
- Never
- Prefer not to respond

11. **How many miles did you drive in the last 12 months?** *
Mark only one oval.

- 0
- 1 - 5,000
- 5,001 - 10,000
- 10,001 - 15000
- 15,001 - 20,000
- 20,001 - 25,000
- 25,001 - 35,000
- 35,001 - 50,000
- 50,001 - 100,000
- > 100,000
- I prefer not to respond

12. **I'm used to** *
Mark only one oval.

- Left-hand traffic (LHT)
- Right-hand traffic (RHT)
- Both LHT and RHT

13. **Do you wear glasses?** *
Mark only one oval.

- Yes
- Sometimes
- No

14 **Do you have any experience in Head mounted Virtual Reality?** *
Mark only one oval.

- Yes
- No

15. **If Yes, then how many times have you experienced it?**
Mark only one oval.

- Only once
- Multiple times
- I have my own Virtual Reality setup at home

16. **Have you experienced a CAVE simulator before in any experiment?** *
Mark only one oval.

- Yes
- No

17. **With the completion of the Pre-Experiment Questionnaire, I am ready to get hands on with the simulator for the practice session and the actual experiment.** *
Mark only one oval.

- I Agree

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Post-Experiment Questionnaire

Thank you for participating in the experiment. Please take some time in a few questions regarding the experiment and your experience with the virtual environment.

* Required

1. **Participant Number (We will write it down for you)** *

___

2. **Did you use glasses during the experiment?** *

   Mark only one oval.

   - ◯ Yes
   - ◯ No

3. **Did you feel that you needed glasses during the experiment?** *

   Mark only one oval.

   - ◯ Yes
   - ◯ No

4. **Where did you first look when the vehicle was approaching?** *

   Mark only one oval.

   - ◯ Grill
   - ◯ Windshield
   - ◯ Bottom of car
   - ◯ Top of car
   - ◯ Can't really say where

Thinking about the overall performance of the automated driving system you just experienced, please rate the following 3 statements.

5. **The 'speed' maintained by the automated vehicle felt:** *

   Mark only one oval.

	1	2	3	4	5	
Too slow	◯	◯	◯	◯	◯	Too fast

e

6 **The 'Stopping distance' maintained by the automated vehicle felt:** *
Mark only one oval.

	1	2	3	4	5	
Uncomfortable	⬭	⬭	⬭	⬭	⬭	Comfortable

7. **The 'Stopping distance' maintained by the automated vehicle felt:** *
Mark only one oval.

	1	2	3	4	5	
Unsafe	⬭	⬭	⬭	⬭	⬭	Safe

External Light band Questionnaire

You must have experienced 3 different types of external light bands. Please rate the visibility of the light band from your experience in the experiment as below. The image of the car with each light band is shown just as a reference.

Automated car with blue light band

8. **As shown above, how would you rate the visibility of the external light band (blue) display cue from the car?** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not at all visible	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Clearly visible

9 **How interactive do you think the light band was?** *

Mark only one oval.

	1	2	3	4	5	
Not at all	◯	◯	◯	◯	◯	Highly interactive

10. **How predictable was the vehicle behavior with the light band ON?** *

Mark only one oval.

	1	2	3	4	5	
Not at all	◯	◯	◯	◯	◯	Highly predictable

Automated car with white light band

11. **As shown above, how would you rate the visibility of the external light band display (white) cue from the car?** *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not at all visible	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Clearly visible

12. **How interactive do you think the light band was?** *

Mark only one oval.

	1	2	3	4	5	
Not at all	◯	◯	◯	◯	◯	Highly interactive

13 **How predictable was the vehicle behavior with the light band ON?** *
Mark only one oval.

	1	2	3	4	5	
Not at all	◯	◯	◯	◯	◯	Highly predictable

Automated car with white light band on top and on the front

14. **As shown above, how would you rate the visibility of the external light band display cue (white +) from the car?** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not at all visible	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Clearly visible

15. **How interactive do you think the light band was?** *
Mark only one oval.

	1	2	3	4	5	
Not at all	◯	◯	◯	◯	◯	Highly interactive

16. **How predictable was the vehicle behavior with the light band ON?** *
Mark only one oval.

	1	2	3	4	5	
Not at all	◯	◯	◯	◯	◯	Highly predictable

Appendix E:
Main Study – Pre-experiment questionnaire

Pre-Experiment Questionnaire

Thank you for agreeing to participate. Please bear some patience in filling out this questionnaire before we start with the experiment. This shouldn't take more than 3 minutes.

* Required

1. **Participant Number (We know it. So you needn't worry about this)** *

   ____

2. **What's your age?** *

   ____

3. **What's your gender?** *
   Mark only one oval.
   - ◯ Male
   - ◯ Female
   - ◯ Prefer not to say
   - ◯ Other: ______________________

4. **What's your Nationality?** *

   ____

5. **How many times do you walk outside in an average day?** *
   Mark only one oval.
   - ◯ Never
   - ◯ Rarely (0 - 2 times a day)
   - ◯ Often (2 - 4 times a day)
   - ◯ Frequently (4+ times a day)

6. **What time range best describes your daily walking time?** *
   Mark only one oval.
   - ◯ 0 -15 minutes
   - ◯ 15 - 30 minutes
   - ◯ 30 - 45 minutes
   - ◯ 45 - 60 minutes
   - ◯ > 60 minutes

7. **What is the main reason for your walking trips?** *
Mark only one oval.

- Commuting
- Leisure
- Both Commuting and Leisure

8. **How long have you been living in the UK?** *
Mark only one oval.

- Less than a Year
- 1 - 5 years
- 5 - 10 years
- More than 10 years

9. **Do you possess a drivers' licence? If Yes, specify the year you got it. (e.g. Yes, 2012 or No)** *

10. **How often do you drive in a month?** *
Mark only one oval.

- Every day
- Just Weekdays
- Just weekends
- Once per week
- Only once
- Never
- Prefer not to respond

11. **How many miles did you drive in the last 12 months?** *
Mark only one oval.

- 0
- 1 - 5,000
- 5,001 - 10,000
- 10,001 - 15000
- 15,001 - 20,000
- 20,001 - 25,000
- 25,001 - 35,000
- 35,001 - 50,000
- 50,001 - 100,000
- > 100,000
- I prefer not to respond

12. **I'm used to** *
Mark only one oval.

- Left-hand traffic (LHT) (Driving on left lane)
- Right-hand traffic (RHT) (Driving on right lane)
- Both LHT and RHT

13. **Do you wear glasses?** *
Mark only one oval.

- Yes
- Sometimes
- No

14. **Do you have any experience in Head mounted Virtual Reality?** *
Mark only one oval.

- Yes
- No

15. **If Yes, then how many times have you experienced it?**
Mark only one oval.

- Only once
- Multiple times
- I have my own Virtual Reality setup at home

16. **Have you participated before in any experiment here in the HIKER?** *
Mark only one oval.

- Yes
- No

17. **With the completion of the Pre-Experiment Questionnaire, I am ready to get hands on with the simulator for the practice session and the actual experiment.** *
Mark only one oval.

- I Agree

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Appendix F:
Main Study – Post-experiment Questionnaire

Post-Experiment Questionnaire

Thank you for participating in the experiment. Please take some time in a few questions regarding the experiment and your experience with the virtual environment.

* Required

1. **Participant Number (We will write it down for you)** *

   ____

2. **Did you use your spectacles during the experiment?** *

   Mark only one oval.

   ◯ Yes
   ◯ No

3. **Did you feel that you needed to wear your spectacles during the experiment?** *

   Mark only one oval.

   ◯ Yes
   ◯ No

4. **Where did you first look when the vehicle was approaching?** *

   Mark only one oval.

   ◯ Front grill
   ◯ Windshield
   ◯ Bottom of car
   ◯ Top of car
   ◯ Can't really say where

5. **What information from the vehicle, if any, do you generally use to decide if it is safe to cross the road? Rate how important each of the factors are, leaving the factor blank if you do not use the information.**

   Mark only one oval per row.

	Unimportant	Slightly unimportant	Neutral	Slightly important	Important
Speed	◯	◯	◯	◯	◯
Distance	◯	◯	◯	◯	◯
Braking	◯	◯	◯	◯	◯
External cues	◯	◯	◯	◯	◯
Vehicle trajectory	◯	◯	◯	◯	◯
Turn indicator	◯	◯	◯	◯	◯
Waited for vehicle to pass	◯	◯	◯	◯	◯

6. **What information from the driver, if any, do you generally use to decide if it is safe to cross the road? Rate how important each of the factors are, leaving the factor blank if you do not use the information.**

Mark only one oval per row.

	Unimportant	Slightly unimportant	Neutral	Slightly important	Important
Watching driver					
Mutual Eye contact					
Hand gesture					
Head nod					
Head movement to the side					

7. **Is there any other information you generally use to determine how safe it was to cross? (To be completed if you answered the above two questions)**

8. **Who do you think has priority while crossing at an un-signalized junction?** *

Mark only one oval.

- You
- The driver

9. **During the experiment, what information from the vehicle, if any, did you use to decide it was safe to cross? Rate how important each of the factors are, leaving the factor blank if you do not use the information.**

Mark only one oval per row.

	Unimportant	Slightly unimportant	Neutral	Slightly important	Important
Speed					
Distance					
Braking					
eHMI (Light band)					

Thinking about the overall performance of the automated driving system you just experienced, please rate the following 3 statements.

10. **The 'speed' maintained by the automated vehicle felt:** *

Mark only one oval.

	1	2	3	4	5	
Too slow						Too fast

11. **The 'Stopping distance' maintained by the automated vehicle felt:** *
Mark only one oval.

	1	2	3	4	5	
Uncomfortable	◯	◯	◯	◯	◯	Comfortable

12. **The 'Stopping distance' maintained by the automated vehicle felt:** *
Mark only one oval.

	1	2	3	4	5	
Unsafe	◯	◯	◯	◯	◯	Safe

External Light band Questionnaire

White + front light band as seen in the experiment

13. **How would you rate the visibility of the external light band display cue from the car?** *
Mark only one oval.

	1	2	3	4	5	
Not at all visible	◯	◯	◯	◯	◯	Clearly visible

14. **How interactive do you think the light band was?** *
Mark only one oval.

	1	2	3	4	5	
Not at all	◯	◯	◯	◯	◯	Highly interactive

15. **How predictable was the vehicle behavior with the light band ON?** *

Mark only one oval.

	1	2	3	4	5	
Not at all	◯	◯	◯	◯	◯	Highly predictable

16. **Overall, how much do you trust the external light band with respect to the yielding behavior of the vehicle?** *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
No trust at all	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Very high trust

17. **The vehicle yielded sometimes with the light band ON and sometimes without the light band. Did this difference affect your crossing behavior? If so, then why?** *

18. **Did the fact that you already know that the vehicle is automated and the information that the light band actually means yielding behavior affect your crossing decision and behavior? If so, then how?** *

19. **To what extent do you think that the usage of this light band actually helps people to comprehend the yielding behavior correctly in real world.** *

Mark only one oval.

	1	2	3	4	5	
Not at all	◯	◯	◯	◯	◯	Easily comprehensive

20. **Do you have any comments on the scenario of the experiment such as realism, daily interactions, speed, external cues, etc. ? If not, you can leave this blank and continue to the next section**

Presence Questionnaire

21. **How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Not Proficient	◯	◯	◯	◯	◯	◯	◯	Very Proficient

22. **How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Completely

23. **How closely were you able to examine objects?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Very closely

24. **How much did the auditory aspects of the environment involve you?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Completely

25. **How quickly did you adjust to the virtual environment experience?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Less than one minute

26. **How natural was the mechanism which controlled movement through the environment?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Extremely artificial	◯	◯	◯	◯	◯	◯	◯	Completely Natural

27. **Were you able to anticipate what would happen next in response to the actions that you performed?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Completely

28. **How responsive was the environment to actions that you initiated (or performed)?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Not responsive	◯	◯	◯	◯	◯	◯	◯	Completely responsive

29. **How involved were you in the virtual environment experience?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Not invloved	◯	◯	◯	◯	◯	◯	◯	Completely engrossed

30. **How natural did your interactions with the environment seem?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Extremely artificial	◯	◯	◯	◯	◯	◯	◯	Completely Natural

31. **How compelling was your sense of objects moving through space?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Very compelling

32. **How much did the visual aspects of the environment involve you?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Completely

33. **How much delay did you experience between your actions and expected outcomes?** *
Mark only one oval.

	1	2	3	4	5	6	7	
No delays	◯	◯	◯	◯	◯	◯	◯	Long delays

34. **How much did your experiences in the virtual environment seem consistent with your real world experiences?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Not consistent	◯	◯	◯	◯	◯	◯	◯	Very consistent

35. **How completely were you able to actively survey or search the environment using vision?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Completely

36. **How much did the control devices/ motion sensors interfere with the performance of assigned tasks or with other activities?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Interfered greatly

37. **How well could you examine objects from multiple viewpoints?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Extensively

38. **How compelling was your sense of moving around inside the virtual environment?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Not compelling	◯	◯	◯	◯	◯	◯	◯	Very compelling

39. **How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Prevented task performance

40. **How much were you able to control events?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	◯	◯	◯	◯	◯	◯	◯	Completely

41. **Do you have any comments on the experience in the CAVE virtual environment? If not, you can skip this question.**

42. **The experimenters nor Delft University of technology nor University of Leeds is responsible for any of the unusual interactions I do with regular traffic after this experiment.** *

Mark only one oval.

◯ Yes, I understand.

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